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Study of Optical Fiber Design Parameters in Fiber Optics Communications

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Abstract: ***Fiber optics is an important part in the telecommunication infrastructure. Large bandwidth and low attenuation are features for the fiber optics to provide gigabit transmission. Nowadays, fiber optics are used widely in long distance communication and networking to provide the required information traffic for multimedia applications. In this paper, the optical fiber structure and the operation mechanism for multimode and single modes are analyzed. The design parameters such as core radius, numerical aperture, attenuation, dispersion and information capacity for step index and graded index fibers are studied, calculated and compared for different light sources.***

Keywords: Step index, Graded index, Numerical aperture, Multimode and single mode fibers.

1. INTRODUCTION

The large amount of data traffic, required for nowadays multimedia applications, increases the demand for a transmission medium with high bandwidth. The large bandwidth, high security, low interference, low attenuation, ease of maintenance, and long life span are features for the fiber optics that enable it to support high data rate services.

An optical fiber is a physical waveguide that used to transmit electromagnetic waves in the optical spectrum. They are used as components in integrated optical circuits, as the transmission medium in long distances for light wave communications, or for biomedical imaging. Fiber Optics can be designed to operate in single-mode or multi-mode depending on the number of lights rays transmitted simultaneously. According to the refractive index distribution, fiber optics can be classified into two types, step index fiber and graded index fiber. Different material can be used in the fabrication of the fiber optics such as glass, polymer, and semiconductors.

The widespread use of fiber optics communication is mainly derived by the rapid increase in the demand for large telecommunication capacity and reliable communication systems. Compared to wireless and copper-wired transmission media, fiber optics technology is more efficient in providing the required information capacity. Due to advance in fiber optics technology, a single optical fiber can be used to carry more data over long distances.

Different techniques can be used to significantly improve the capacity of optical networks such as wavelength division multiplexing [1]. Signal Processing in the optical domain is more efficient than the electrical domain [2]. Therefore it is desired for future optical systems to have the ability of information processing exclusively in the optical domain. Signal processing includes amplification, multiplexing, switching, and filtering. An example of current type of optical communication system that processes the signal in optical domain is Code Division Multiple Access [3]. Despite the advantages of using optical fiber for communication systems, it is vital to conduct further research to improve fiber optics communication systems, and to address a number of challenges facing it [4].

In this paper the analysis of optical fiber is presented and the design parameters is studied and calculated for optics communication system.

2. OPTICAL FIBER ANALYSIS

2.1 Optical Fiber Structure

In the dielectric slab planer waveguide shown in figure (1), the wave travels primarily in the central layer (core of radius a), which has refractive n_1 , this layer is so small often, less than a micrometer that it is referred to as a film, the film is sandwiched between a bottom layer and top layer having indices n_2 .

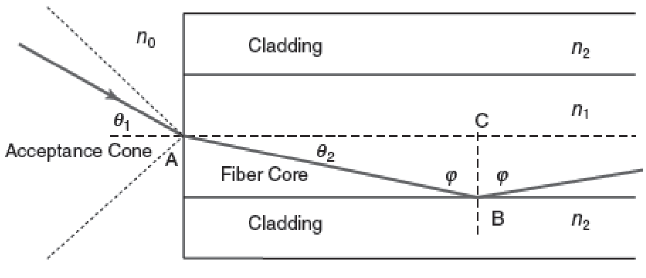

Figure (1): Symmetrical planar waveguide

Light rays are trapped in the film by total internally reflection. The critical angle value $\emptyset_c$ is given by [5]:

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

The angle of incident rays $\emptyset$ in figure (1) must be equal or greater than the critical angle in order the lights propagates continuously through the core of the fiber to the destination. For efficient transmission, the materials used are must has small absorption as in the table some materials refractive indexes.

All ray angles $\emptyset$ for propagating waves lie between $\emptyset_c$and 90°, or $\emptyset_c \leq \emptyset \leq 90^{\circ}$and the corresponding effective refractive indices are in the range

$$n_2 \leq n_{eff} \leq n_1 \qquad (2)$$

Where $n_{eff} = n_1 \sin \emptyset$

Obviously, all the waves having angles greater than $\emptyset_c$ and 90^{o} will enters the fibers core but, actually the numbers of the waves propagates through the fiber will constraint by the following condition:

$$\nabla\emptyset = 2\pi m \qquad (3)$$

Where $\nabla\emptyset$ denoting the round trip phase shift, m is an integer and represents the mode number. Hence the light propagating through the core of the fiber optics in discrete modes, each described by a distinct value of $\emptyset$ (incident rays).This discrete rays are called modes for example when (m = 0, 1, 2), this denotes three lower order modes in the planar dielectric guide. The ray waves of different modes may express as [5]:

$$\tan(\text{ha}+m\pi) = \frac{1}{n_1 \cos\emptyset}\sqrt{n_1^2 \sin^2\emptyset - n_2^2} \qquad (4)$$

Where $h = 2\pi n_1 \cos\emptyset/\lambda$, a represents the core radius thickness and λ is the free-space wavelength of operating frequency.

For higher-ordered modes the solutions (including both even and odd modes) the normalized thickness can be calculated by:

$$\left(\frac{a}{\lambda}\right)_m = \left(\frac{a}{\lambda}\right)_0 + \frac{m}{4n_1 \cos\emptyset} \qquad (5)$$

Where m is a positive integer and represents the mode number. In the boundary as the incident angle,θ_1, approaches θ_{acc}, the internal angle reaches the critical angle for total reflection $\emptyset_c$. Then, we obtain:

$$n_0 \sin\theta_1 = n_1 \cos\emptyset = \sqrt{n_1^2 - n_2^2} = n_1\sqrt{2\Delta} \qquad (6)$$

Where Δ represents fractional reflective indices or

$$\Delta = \frac{n_1 - n_2}{n_1} \qquad (7)$$

The equation (6) describes the angle within which the fiber can accept and propagate light and is referred to as the "Numerical Aperture" (*NA*) that is defined by:

$$NA = n_0 \sin\theta_{acc} \qquad (8)$$

When the medium with refractive index n_0 is air, the equation (7) for the *NA* of the glass fiber is simplified to

$$NA = \sin\theta_{acc} = \sqrt{n_1^2 - n_2^2} = n_1\sqrt{2\Delta} \qquad (9)$$

Therefore the acceptance angle can be calculated from eq. (8) as:

$$\theta_{acc} = \sin^{-1} NA \qquad (10)$$

This equation states that for all angles of incident where the inequality 0 $\leq\theta_1\leq\theta_{acc}$ is satisfied the incident ray will propagate within the fiber. The parameter NA is useful measure of light collecting ability of fiber to accept and propagate light within the solid cone distinct by an angle, $2\theta_{acc}$. The highest-ordered mode that can propagate has the value for m given by [5]:

$$m_{high} = \left(\frac{4a}{\lambda}\right)\sqrt{n_1^2 - n_2^2} \qquad (11)$$

Therefore:

$$m_{high} = \left(\frac{4a}{\lambda}\right) NA \qquad (12)$$

Since the lowest-ordered mode has the value of = 0 , therefore the number of propagating TE modes N is the integer value of :

$$N = 1 + \left(\frac{4a}{\lambda}\right) NA \qquad (13)$$

Finally, the condition at cutoff for the mth modes is described by:

$$\left(\frac{a}{\lambda}\right)_{m,cutoff} = \frac{m}{4NA} \qquad (14)$$

Taking into consideration that if $\left(\frac{a}{\lambda}\right)_m > \frac{m}{4NA}$the mth modes will propagate. It is noted that the condition of single mode fiber (first mode or called zero mode) is:

$$\left(\frac{a}{\lambda}\right)_0 < \frac{1}{4NA} \qquad (15a)$$

while the condition of multimode fiber (of m modes) is:

$$\left(\frac{a}{\lambda}\right)_m < \frac{m+1}{4NA} \qquad (15b)$$

Figure (2) shows the six TE and TM modes for n_1=1.48 and n_2=1.46.

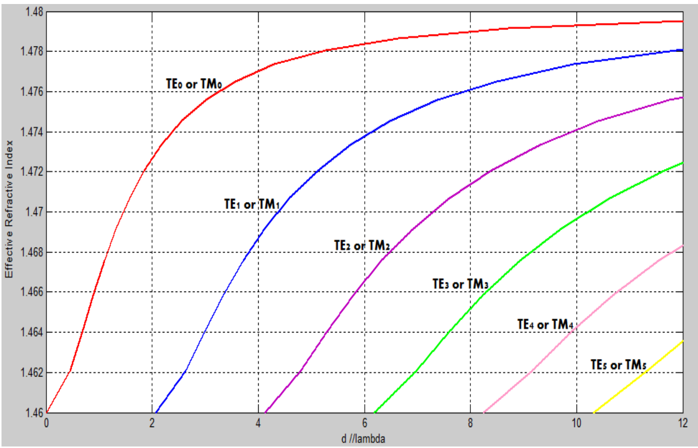

Figure (2): The first six TE_m Modes for planner waveguide (n_1=1.48 and n_2=1.46)

2.2 Modes in optical fiber

Many modes TE and TM modes (transverse electric and transverse magnetic modes) are generated in the cylindrical optical fiber in addition to HE and EH modes which are hybrid, and each contains components of electric and magnetic fields pointing along the fiber axis [6]. In the followings, these modes are discussed according to the types of optical fibers. Three basic types of optical fibers are used in communication systems: (a) Step-index multimode (SIM) fiber, (b) Step-index single mode (SIS) fiber, (c) Graded-index fiber (GI).

(a) The Step Index multimode (SIM) fiber

It consists of a central core where refractive index is n_1, surrounded by a cladding whose refractive index is n_2. Figure (3) illustrates its structure and the possible ray paths.

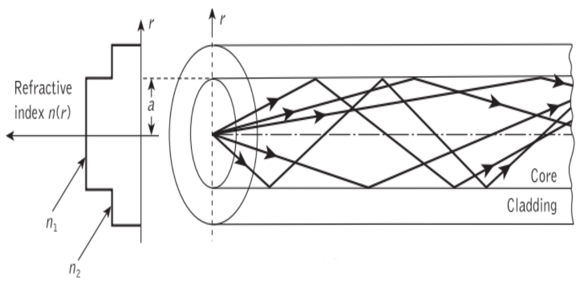

Figure (3): Step index fiber

The modes chart for step index fibers appears in figure (2). This chart is similar to the symmetrical slab mode chart in figure (1). One difference is that the fiber chart has been normalized by plotting the effective refractive index as a function of the parameter v, called the normalized frequency that is giving by [6]:

$$v = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \qquad (16)$$

The chart shows the existence of many modes TE and TM modes in addition to HE and EH modes. Each curve in figure (4) actually represents two modes one orthogonally to the other in transverse plane. For large values of v, many modes will propagate. The number of propagating modes is approximated by:

$$N = \frac{v^2}{2} \qquad (17)$$

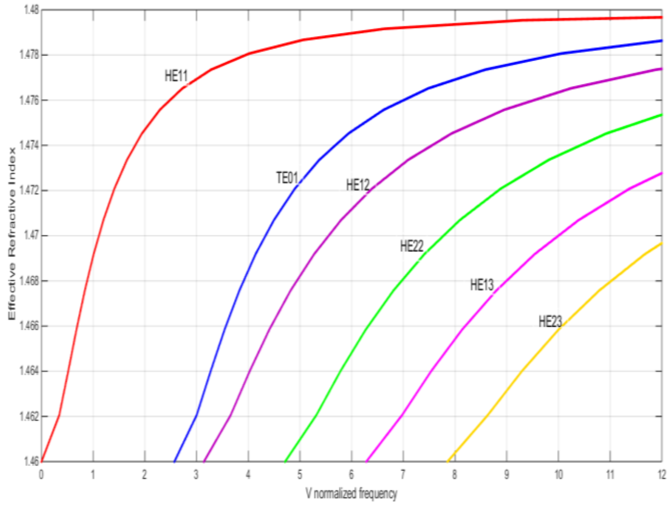

Figure (4): The effective reflective index as a function of normalized frequency v.

(b) Step-index single mode (SIS) fiber

Single-mode propagation is assured if all modes except the HE11 mode are cutoff. Referring to figure (4) it is noticed that this phenomenon will occur if v < 2.405. Combining this result with Eq (16) the core radius is calculated by:

$$\frac{a}{\lambda} < \frac{2.405}{2\pi\sqrt{n_1^2 - n_2^2}} = \frac{2.405}{2\pi NA} \qquad (19)$$

As the condition of single mode propagation. This result is very similar to the single mode condition for the symmetrical slab eqn.(15a). If eqn. (19) is satisfied, then only the HE_{11} mode can travel through the fiber, two orthogonally polarized HE_{11} waves can actually exist in the fiber simultaneously, but they have the same n_{eff} and therefore, travel the same velocity.

(c) Graded Index Fiber

The graded index fiber has a core material whose refractive index decreases continuously with distance r from the axis. This structure, illustrated in figure (5) appears to be quite different from the SIM fiber. The index variation is decreased by:

$$n(r) = n_1\sqrt{1 - 2\left(\frac{r}{a}\right)^{\alpha}\Delta} \quad , \quad r \le a \qquad (20)$$

$$n(r) = n_1\sqrt{1 - 2\Delta} = n_2 \quad , \quad r > a \qquad (21)$$

Where α is the profile parameter which represents the refractive index profile of fiber optics core. When α=2 in eq. (20), the core index becomes:

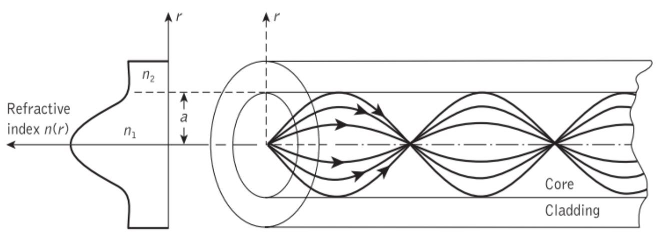

Figure (5): The multimode graded index fiber

$$n(r) = n_1\sqrt{1 - 2(\frac{r}{a})^2\Delta} \quad (22)$$

This index distribution is called the parabolic profile. For parabolic profile the numerical aperture is determined as [5]:

$$NA = n_1(2\Delta)^{1/2}\sqrt{1 - (\frac{r}{a})^2} \quad (23)$$

This function has been plotted in figure (6) for n_1=1.48 and Δ=0.0135.

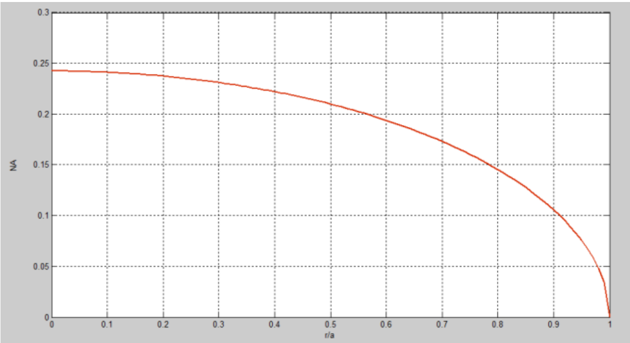

Figure (6): Numerical aperture NA as a function of r forn$_1$=1.48 and Δ=0.0135.

The number of modes for parabolic profile is approximated by[ref.]:

$$N = \frac{v^2}{4} \quad (25)$$

The condition for graded-index single mode propagation is given by[ref]:

$$\frac{a}{\lambda} < \frac{1.4}{\pi\sqrt{n_1(n_1 - n_2)}} \quad (24)$$

A more precise analysis changes the factor 1.4 to 1.2.

3. CALCULATIONS OF DESIGN PARAMETERS

3.1 Operating Wavelength

According to (ITU) the International Telecommunications Union regulations the bands allocated for both intermediate-range and long-distance optical fiber communications are specified by the letters O, E, S, C, L and U, which are defined in Table 1. The more common usable bands are O-band and C-band giving minimum attenuation through the fiber length. The lowest attenuation happens at wavelengths around 1.310 µm and 1.550 µm. Therefore, the laser source manufacturer's has designed a various types of laser sources for these designated bands, where attenuation is less than 0.6dB per km.

Table 1: ITU regulations bands [6]

Name	**ITU band**	**Wavelength λ µm**
Original band	O-band	1.260 to 1.360
Extended band	E-band	1.360 to1.460
Short band	S-band	1.460 to 1.530
Conventional band	C-band	1.530 to 1.565
Long band	L-band	1.565 to 1.625
Ultralong band	U-band	1.625 to 1.675

3.2 Core Radius

The size of optical fibers plays crucial role in the light wave propagation through fiber. Therefore, radius of the core is significant to decide mode of propagation in fiber as:

$\frac{a}{\lambda} < \frac{2.405}{2\pi NA}$ for step-index single mode fiber.

$\frac{a}{\lambda} < \frac{1.4}{\pi\sqrt{n_1(n_1 - n_2)}}$for graded-index single mode fiber,

otherwise the multi modes will propagate. The thickness/diameter of the core can be measured in spite of measurement of radius. The standard core sizes are 50 µm and 62.5 µm for multi-mode fiber while 5-10 µm for single mode fiber.

3.3 Numerical aperture

Numerical aperture (NA) is a light gathering property of optical fiber, which gives the quantity of light that brought into the center of optical fiber in terms of incidence angle according to equation (9). The value of the numerical aperture is about 5% lower than the value of the maximum theoretical numerical aperture *NAmax* which is resulting from a refractive index measurements trace of the core $n_1$and cladding n_2 .

3.3 Acceptance Angle

It is a semi vectorial angle that formed by the set of incident rays at the center of fiber, which helps to decide the size of core or the numerical aperture according to equation (10).

3.4 Attenuation

The most important transmission characteristic is attenuation or loss. The transmission losses bound the total length of the fiber communication system.

Rayleigh scattering losses is proportional to λ^{-4}, it becomes increasingly important as the wavelength diminishes, the Rayleigh scattering loss can be approximated by the expression:

$$L_{sc} = 1.7(\frac{0.85}{\lambda})^4 \quad (13)$$

Where λ is in micrometer and L_{sc} is the loss in dB/km due to Rayleigh scattering. It is clear that the scattering severely restricts use of fibers at short wavelength below 0.8 μm. Glass fibers generally have lower absorption than plastic fibers, so they are preferred for long-distance communication.

3.5 Dispersion

The distortion of digital and analog signals which, are transmitted in optical fibers results from dispersion. When fiber optic transmission is implemented with its essential part which involves some form of digital modulation, due to dispersion mechanisms within the fiber the transmitted light pulses spreads as they travel along the channel. It can say that the dispersion is a light spread out during transmission on the fiber. The dispersion may be categorized into two major types [7]: **intermodal (modal)dispersion** which exists only in multimode fibers and **intra modal (chromatic) dispersion** which exists in all types of fibers (single mode and multimode) which basically divided into types: Waveguide dispersion and Material.

Waveguide dispersion: The optical fiber can be considered as circular wave guide where refractive index varies with modes of propagation with wavelength causes wave guide dispersion.

Material dispersion: The refractive index of core causes the changes in the wavelength/frequency called material dispersion. If narrow pulse passes through fiber, causes broadening of pulse width due to material property. It can be overcome by highly monochromatic source of light. The single mode fibre could reduce the material dispersion to maximum extent.

The refractive index of core causes the changes in the wavelength/frequency called material dispersion. If narrow pulse passes through fiber, causes broadening of pulse width due to material property. It can be overcome by highly monochromatic source of light. The single mode fiber could reduce the material dispersion to maximum extent.

The total **chromatic dispersion** could be expressed as [7]:

$$\Delta_c\left(\frac{\tau}{L}\right) = -\left(M_m + M_g\right)\Delta\lambda \quad (26)$$

Where M_m is the material dispersion, M_g is the waveguide dispersion and Δλ is the source spectral width. A useful analytic approximation in this range for silica fiber is:

$$M_m = \frac{M_O}{4}\left(\lambda - \frac{\lambda_O^4}{\lambda^3}\right) \quad (27)$$

Where M_O is approximately (-0.095 psec./(nm^2.km)) and λ_o is the zero dispersion wavelength equal to 1300nm.Values of M_O and λ_o are often given by the manufacturer.

Distortion in Step Index Fiber

Signals are distorted in SI fiber by material and waveguide dispersion and by multimode pulse spreading. The amount of multimode pulse spreading (due to **modal dispersion**) in a dielectric slab was found by:

$$\Delta_{mod}\left(\frac{\tau}{L}\right) = \frac{n_1\Delta}{c} = \frac{NA^2}{2cn_1} \quad (28)$$

The total pulse spreading Δτ, resulting both from chromatic dispersion $\Delta_c\left(\frac{\tau}{L}\right)$ and from modal one is given by:

$$(\Delta\tau)^2 = (\Delta\tau)^2_{mod} + (\Delta\tau)^2_c \quad (29)$$

Where $(\Delta\tau)_{mod}$ is the multimode dispersive pulse spread and $(\Delta\tau)_c$ is the chromatic dispersive spread.

Distortion in Graded Index Fiber

Graded index fiber produces much less multimode distortion than do SI fibers. An approximate expression for modal pulse in a graded index fiber is

$$\Delta_{mod}\left(\frac{\tau}{L}\right) = \frac{n_1\Delta^2}{2c} \quad (30)$$

Generally the total modal pulse spread can be written as [5]:

$$\Delta\tau = L\,\Delta_{mod}\left(\frac{\tau}{L}\right) \quad \text{for} \quad L \le L_e \quad (31)$$

Or

$$\Delta\tau = \sqrt{LL_e}\Delta_{mod}\left(\frac{\tau}{L}\right) \quad \text{for} \quad L \ge L_e \quad (32)$$

Where $\Delta_{mod}(\tau/L)$ is the spread per unit length in the linear region and L_e represents equilibrium length and is taken as 1km.

3.5 Information Capacity

The information capacity of any fiber optic communication system limits by pulse spreading. The maximum allowable pulse spread requires Δ (τ) ≤ T/2 to avoid the overlaps occurring between the sequential pulses, and then the modulation frequency f is limited by [5]:

$$f = \frac{1}{T} \le \frac{1}{2\Delta\tau} \quad (33)$$

Therefore the optical bandwidth BW_{op} of the fiber is:

$$BW_{op} = \frac{0.5}{\Delta\tau} \quad (34)$$

While the electrical bandwidth BW_{el} is calculated from [5]:

$$BW_{el} = \frac{0.35}{\Delta\tau} \quad (35)$$

which is equal to the data rate (bits per second) of return to zero code format:

$$R_{RZ} = \frac{0.35}{\Delta\tau} \quad (36)$$

while the data rate of non-return to zero code format is given by [5]:

$$R_{NRZ} = \frac{0.7}{\Delta\tau} \quad (37)$$

4. RESULTS AND DISCUSSION

For this study, different fibers are selected to determine their design parameters and to compare the results with those of different sources. The sources are considered to be light emitting diode LED and laser diode.

Firstly, it is chosen different structures for step index fibers representative of all glass, plastic cladded silica fiber PCS, and all plastics constructions. Numerical aperture, acceptance angles, and fractional refractive index changes are computed using eqs.(7, 9 and 10) and listed in Table 2.

Table 2: Typical Step Index Fiber Characteristics

Construction	Core n_1	Cladding n_2	Δ	NA	θ_{acc}
All glass	1.48	1.46	0.0135	0.2425	14°
PCS	1.46	1.4	0.0411	0.4142	24.47°
All plastic	1.49	1.41	0.0537	0.4817	28.79°
AlGaAs	3.6	3.55	0.0139	0.5979	36.72°
Single Mode	1.465	1.46	0.0034	0.12	6.89°

For different light sources for various types of fibers, the fiber losses are calculated according to eq.(13) and the characteristics of the studied fibers are illustrated in Table 3.

Table 3: Characteristics of studied fibers.

Description		Core size μm	NA	Source	λ μm	Loss dB/km
Glass Multi Mode	SI	50	0.24	LED	850	1.7
	GI	50	0.24	LED	850	1.7
	GI	50	0.24	LED	1320	0.29
	GI	50	0.24	LED	1550	0.15
	GI	50	0.24	LED	1600	0.15
PCS	SI	200	0.41	LED	800	2.2
Glass Single Mode	SI	5	0.12	LD	820	1.96
	GI	5	0.12	LD	1550	0.15
	SI	10	0.12	LD	1600	0.14

It is noted that the losses of longer wavelength are lower than those of shorter ones. The plastic fibers are cheap and used for shorter distances while glass fibers are used for long distances due to their low attenuation.

Now, the information capacities for step index and graded index fibers are calculated according to eq.(29, 34-37) for different sources and listed in Table 4 and Table 5 respectively.

Table 4: Information capacity for step index fibers.

Source	λ μm	Δλ nm	Δ(τ/L) ns/km	$BW_{op} \times L$ GHz .km	$BW_{el} \times L$ GHz .km	Bit rate $R_{RNZ} \times L$ Gbps. km	Bit rate $R_{RZ} \times L$ Gbps. km
LED	0.85	20	66.24	0.008	0.005	0.011	0.005
LED	1.32	50	66.22	0.008	0.005	0.011	0.005
LED	1.55	50	23.3	0.022	0.015	0.030	0.015
LED	1.60	30	16.65	0.030	0.021	0.042	0.021
LD	0.82	1	0.10	5	3.7	7	3.7
LD	1.55	1	0.02	25	17.5	35	17.5

Table 5: Information capacity for graded index fibers.

Source	λ μm	Δλ nm	Δ(τ/L) ns/km	$BW_{op} \times L$ GHz .km	$BW_{el} \times L$ GHz .km	Bit rate $R_{RNZ} \times L$ Gbps. km	Bit rate $R_{RZ} \times L$ Gbps. km
LED	0.85	20	1.86	0.269	0.188	0.377	0.188
LED	1.32	20	0.45	1.111	0.778	1.555	0.778
LED	1.55	50	1.03	0.486	0.34	0.68	0.34
LED	1.60	30	0.78	0.641	0.45	0.897	0.45
LD	0.82	1	0.05	10	7	14	7
LD	1.55	1	0.015	33	23	47	23

From the previous tables, it is clear that the data rate of the transmission increases when the fiber dispersion Δ(τ/L) decreases. The multimode fibers have generally good characteristics compared with the others and the graded index fibers especially of laser diode source have high performance related to the bit rate.

5. CONCLUSIONS

The large amount of data traffic, required for nowadays multimedia applications, increases the demand for a transmission medium with high bandwidth. The analysis of optical fiber structure has been introduced in this paper and its design parameters, such as core radius, numerical aperture, attenuation, dispersion and information capacity have been studied and calculated for different sources. In general, multimode optical fiber continues to be the most cost-effective choice for enterprise and data center applications up to 1km range. Beyond that, single-mode optical fiber of LD source is necessary for high bit rate.

Despite the advantages of using optical fiber for communication systems, such as the large bandwidth, high security, low interference, low attenuation, ease of maintenance and long life span. It is vital to conduct further research to improve fiber optics communication systems, and to address a number of challenges facing it.

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