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Design and Simulation of a Low Loss Single Mode Optical Fiber

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Abstract

A low loss single mode optical fiber was designed and simulated.The simulation is done by MATLAB Software. From the designed and simulated result we have found that at 1310 nm and 1550 nm wavelength of light (a) the mode field diameter becomes 8.84 μm and 10.06 μm (b) scattering loss is 0.28 dB/km and 0.147 dB/km (c) absorption loss is 0.661 μdB/km and 0.020 dB/km (d) bending loss is 0.06 dB/km and 0.029 dB/km. As a result total fiber loss becomes 0.34 dB/km at 1310 nm wavelength of light and 0.192 dB/km at 1550 nm wavelength of light. Furthermore the designed and simulated result yields the chromatic dispersion is 18.2 ps/nm.km at 1550 nm wavelength of light. Zero chromatic dispersion occur around at 1310 nm wavelength of light that is why chromatic dispersion is calculated at 1550 nm wavelength of light. The bandwidth of our designed fiber is 13.7 Gbps. Finally a comparative study between our designed fiber and typical fiber available in the market has been done. Comparison showing better performance of our designed fiber than the fiber available in the market.

Keywords: Cutoff Wavelength, Mode Field Diameter (MFD), Fiber Loss, Dispersion, Bandwidth.

1. Introduction

In telecommunications and data communications, success of a given optical system depends directly on the choice of fiber parameters. The objective of this paper is to (i) study the optical properties of single mode fiber (SMF) parameters such as cutoff wavelength, mode field diameter, fiber losses, dispersions and bandwidth for 1km fiber length, (ii) design and simulation of a single mode optical fiber that transmit optical power within the fiber with very low loss, low dispersion and higher bandwidth and (iii) the comparison between our designed fiber and typical commercially available fiber in the market. The simulation is performed by the MATLAB Software. In this paper we report the design of single mode silica fiber. The parameters reported in this paper are useful in assessing the design fibers for long haul communication systems.

2. Theoretical considerations of the designed optical fiber

2.1 Cutoff Wavelength

The cutoff wavelength of a single mode fiber is the wavelength above which the fiber propagates only the fundamental mode. The cutoff wavelength for single mode fiber is defined as [1]:

$$\lambda c = \frac{2\pi(an_1)\sqrt{(2\Delta)}}{V} \tag{1}$$

where ‘a’ is the radius of core, n_1 is the refractive index of core, V is normalized frequency. Thus for a given index profile, the cutoff wavelength λc depends on the core radius and relative index difference (Δ). The dependence of λc, on ‘a’ and ‘Δ’, play important role in the design of single mode fibers.

2.2 Mode Field Diameter

Mode field diameter ($2F_d$) shows the light guiding property of the fiber by indicating the boundary where the electric field of the optical wave falls to 36.8% of the core center [2]. In single mode fiber, a

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significant amount of the power resides outsides the fiber core. The theoretical value of mode field diameter ($2F_d$) is given by [2],

$$2F_d = 2a\left[0.65 + 0.434\left(\frac{\lambda}{\lambda c}\right)^{3/2} + 0.0149\left(\frac{\lambda}{\lambda c}\right)^{6}\right] \quad (2)$$

where, λ = operating wavelength, λc= cutoff wavelength, 2a = core diameter.

2.3 Fiber Losses

Losses in the fiber result in a reduction in the light power and, thus, reduce system bandwidth, information transmission rate, efficiency, and overall system capacity. The dominant fiber losses in our designed fiber are as follows:

2.3.1 Scattering Loss

Basically, scattering losses are caused by the interaction of light with density fluctuations within a fiber. Rayleigh scattering is the main loss mechanism between the ultraviolet and infrared regions [3, 4, 5]. For a single component glass Rayleigh scattering coefficient, γ is given by [4, 6]:

$$\gamma = \frac{8\pi^3 n^8 P^2 \beta_c K T_F}{3\lambda^4} \quad (3)$$

where, n is the refracting index, λ is the wavelength, P is average photoelastic coefficient, βc is isothermal compressibility at T_F , K is Boltzman constant, T_F is Fictative temperature. Silica has an estimated fictive temperature of 1400K with an isothermal compressibility of $7\times10^{-11}\ m^2N^{-1}$.The refractive index and photoelastic coefficient of the silica are 1.4675 and 0.286 respectively. Hence:

$$\gamma = \frac{1.96 \times 10^{-28}}{\lambda^4} \quad (4)$$

Furthermore Rayleigh scattering coefficient is related to the transmission loss factor *Γ* of the fiber following the relation of fiber length L:

$$\Gamma = \exp(-\gamma \times L) \quad (5)$$

Thus the scattering loss due to Rayleigh scattering given by [4] is,

$$\text{Scattering loss} = 10\log\left(\frac{1}{\Gamma}\right) \quad (6)$$

2.3.2 Absorption Loss

Absorption loss in optical fibers is caused by imperfections in the atomic structure of the fiber material, the intrinsic or basic fiber-material properties and the extrinsic fiber-material properties [7]. The ultraviolet loss contribution in dB/km at any wavelength can be expressed empirically as a function of the mole fraction x of GeO_2 as [7],

$$\alpha_{uv} = \frac{154.2x * 10^{-2} \exp\left(\frac{4.63}{\lambda}\right)}{46.6x + 60} \quad (7)$$

The ultraviolet loss is small compared with scattering loss in the near infrared region. Extrinsic absorption is caused by the electronic transition of these metal ions from one energy level to another. Extrinsic absorption also occurs when hydroxyl ions (OH^{-1}) are introduced into the fiber. Recently the amount of water (OH^{-1}) impurities present in a fiber can be effectively eliminated by the Lucent Technology [7]. An empirical expression for the infrared absorption loss in dB/km for GeO_2-SiO_2 glass is [7]:

$$\alpha_{absorp} = 7.81 * 10^{11} * \exp\left(-\frac{48.48}{\lambda}\right) \quad (8)$$

2.3.3 Bending Loss

Bending loss is classified according to the bend radius of curvature: macrobend loss or microbend loss. Macrobend losses are observed when a fiber bend's radius of curvature is large compared to the fiber diameter. Microbends are small microscopic bends of the fiber axis that occur mainly when a fiber is cabled [6]. Macrobend loss is the dominant loss in single mode fiber. For single mode fiber, macrobending loss is given by [2]:

$$L_b(dB/km) = A * \frac{\exp\left[\frac{m1(2.748 - m2\,\lambda)^3}{\lambda c}\right]}{\lambda^2} \quad (9)$$

$$\text{Here, } A = 60\pi\left(\frac{N}{L}\right) * \Delta^{\frac{1}{4}} * R^{\frac{1}{2}/2} * \lambda_c^{\frac{3}{2}} \quad (10)$$

$$m1 = -0.705 * (\Delta)^{\frac{3}{2}} * R \quad (11)$$

$$m2 = \frac{0.996}{\lambda c} \quad (12)$$

Here L_b is the fiber length in km, N is the number of turns, λ and λc are in µm, R is in µm, Δ is the fractional difference in the index of refraction of the core and cladding .

2. 4 Dispersions

Dispersion is the spreading of light pulse as its travels down the length of an optical fiber.

Dispersion limits the bandwidth or information carrying capacity of a fiber [8]. Dispersion is the time distortion of an optical signal that result from the time of flight difference of different components of that signal, typically resulting in pulse broadening [9].In a single mode fiber two types of dispersions are observed i.e. Chromatic dispersion and Polarization mode dispersion. A single mode fiber carries only one mode and therefore does not experience intermodal dispersion [10, 11].

2.4.1 Chromatic Dispersion

Chromatic dispersion is an important property which causes different wavelengths of light to travel at different velocities [12]. The total dispersion due to both the material and waveguide effects is called the chromatic dispersion [1].The chromatic-dispersion parameter in a single mode fiber is the sum of the material and waveguide dispersion [10], so that,

$$\mathrm{D}(\lambda) = \mathrm{D_{mat}}(\lambda) + \mathrm{D_{wg}}(\lambda) \qquad (13)$$

Pulse spreading caused by the chromatic dispersion. Δtchrom is given by [10]:

$$\Delta \mathrm{t_{chrom}}/\mathrm{L} = \mathrm{D}(\lambda) * \Delta\lambda \qquad (14)$$

Where, D(λ) is the chromatic dispersion parameter of the fiber and Δλ is the spectral width of the light source. The chromatic-dispersion parameter in a single mode fiber is given by [10]:

$$\mathrm{D}(\lambda) = \mathrm{S_o}\frac{\lambda\left[1 - \left(\frac{\lambda}{\lambda_0}\right)^4\right]}{4} \qquad (15)$$

where, λ_0 is the zero dispersion wavelength and $\mathrm{S_o}$ is the zero dispersion slope.

2.4.2 Polarization Mode Dispersion

Pulse spreading caused by a change of fiber polarization properties is called polarization mode dispersion (PMD). This pulse spreading, ΔtPMD, can be calculated [10] as follows:

$$\Delta \mathrm{t_{PMD}} = \mathrm{D_{PMD}}\sqrt{\mathrm{L}} \qquad (16)$$

Where, $\mathrm{D_{PMD}}$ is the coefficient of polarization-mode dispersion measured in ps/√km, and L is the fiber length in km.

2.5 Bandwidth

Since fiber-optic communications technology uses the terms bandwidth and bit rate interchangeably, we will follow this pattern. The bit rate, BR of a fiber link is defined [10] as,

$$\mathrm{BR} < \frac{1}{4\Delta \mathrm{t}} \qquad (17)$$

Where, Δt is the dispersion-induced-pulse spreading. Let's now calculate BR limited by the chromatic dispersion equation (14) can be rewritten as:

$$\Delta \mathrm{t_{chrom}} = \mathrm{D}(\lambda) * \Delta\lambda \qquad (18)$$

From equation (17) we get,

$$\mathrm{BR_{chrom}} = \frac{1}{[4\,\mathrm{D}(\lambda) * \Delta\lambda * \mathrm{L}]} \qquad (19)$$

Where, $\mathrm{BR_{chrom}}$ is the maximum bit rate limited by the chromatic dispersion. The chromatic dispersion parameter is given by,

$$\mathrm{D}(\lambda) = \mathrm{So}\frac{\lambda\left[1 - \left(\frac{\lambda}{\lambda_0}\right)^4\right]}{4} \qquad (20)$$

In fiber communication technology, the highest bandwidth can be achieved using single mode fibers.

3. Single mode optical fiber designed considerations

To design a single mode fiber we have considered the following fiber parameters. In single mode fiber, the core diameter must satisfy the relation [2] , d <(0.766 λ/NA). The core diameter is 8µm and core radius is 4 µm. The core and cladding refractive indexes are 1.4675 and 1.4622 respectively. The operating wavelength is 1310/1550 nm. Normalize frequency is ≤2.405. Numerical aperture is 0.12 and the total fiber length is one kilometer. The physical layout of our designed single-mode optical fiber is shown in Fig.1.

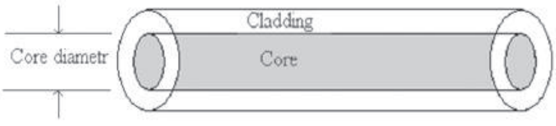

Fig.1. Physical layout of a single-mode optical fiber.

4. Results and Discussion

We simulated our designed fiber using the MATLAB Software. We simulated equation (1) to get the cutoff wavelength. The simulation result shows that the cut-off wavelength of our designed single-mode optical fiber is 1300 nm. This is the shortest wavelength at which a fiber can support single mode operation. In practice, the fibers are designed specifically for the operating wavelength is always longer than cut-off wavelength. We simulated equation (2) to find the mode field diameter of our designed single mode optical fiber. A plot of simulated result of mode field diameter of the fiber corresponding to different wavelength of light is shown in Fig.2.

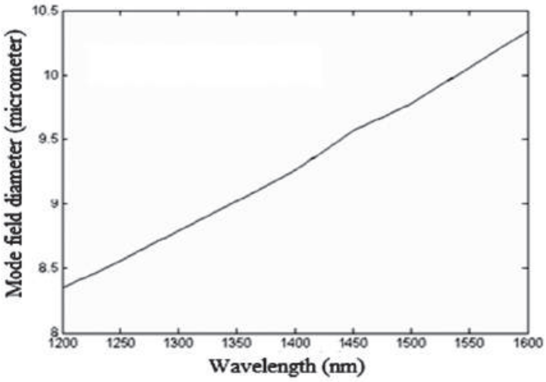

Fig.2. Mode field diameter (μm) Vs Wavelength (nm)

It is observed from Fig.2 that mode field diameter increases as the wavelength increases. At wavelengths 1310 nm and 1550 nm, the mode field diameter becomes 8.84 μm and 10.06 μm respectively. The equations (3), (4), (5) and (6) were simulated to find the scattering loss of the single mode optical fiber. A plot of simulated result of scattering loss of the fiber corresponding to different wavelength of light is shown in Fig.3.

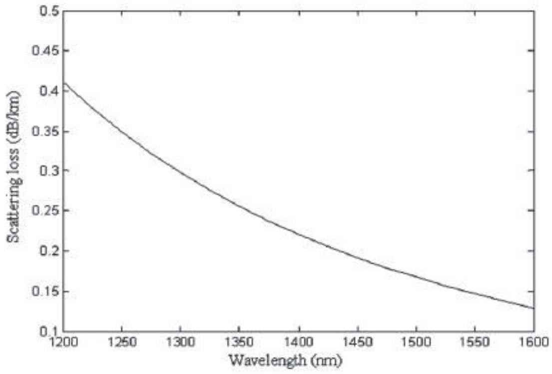

Fig.3. Scattering loss (dB/km) Vs Wavelength (nm).

It is evident from Fig.3 that the scattering loss decreases as the wavelength increases. The scattering loss at 1310 nm wavelength of light is 0.28 dB/km and at 1550 nm wavelength of light is 0.147 dB/km respectively. We simulated equation (8) to find the absorption loss of the single mode fiber. A plot of simulated result of absorption loss of the fiber corresponding to different wavelength of light is shown in Fig.4.

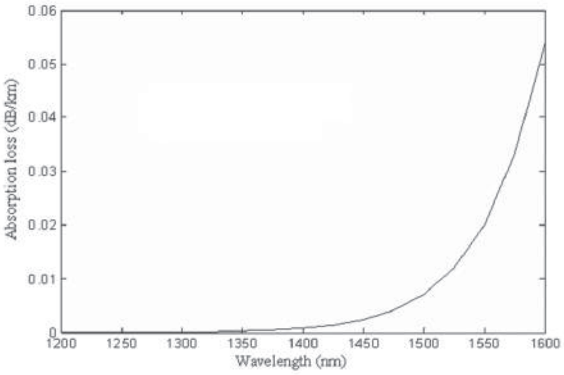

Fig.4. Absorption loss (dB/km) Vs Wavelength (nm)

It is evident from Fig.4 that the absorption loss increases as the wavelength of light increases. The absorption loss at 1310 nm wavelength of light is 0.661 μdB/km and at 1550 nm wavelength of light is 0.020 dB/km respectively. It is clear from Fig.4 that the absorption loss at 1310 nm wavelength of light is significantly very low (0.661 μdB/km) and therefore, is ignored in our designed optical fiber. The absorption loss of our designed fiber is lower than the reported loss because we have considered that the core of the optical fiber is made of ultra-pure low-loss glasses and we also considered that we have eliminated the amount of water (OH^-) impurities present in the fiber using Lucent Technology. The equations (9), (10), (11) and (12) were simulated to find the bending loss of the fiber. A plot of simulated result of bending loss of the fiber corresponding to different radius of curvature of the fiber is shown in Fig.5.

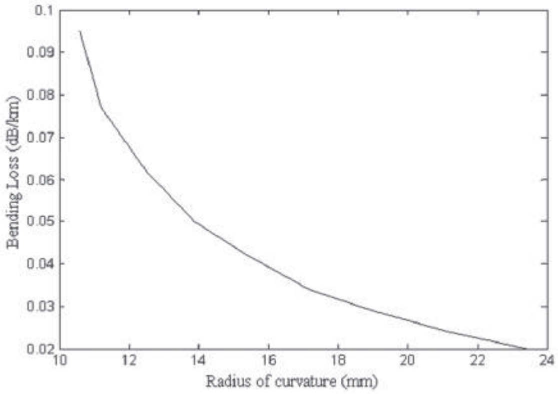

Fig.5. Bending loss (dB/km) Vs radius of curvature (mm)

From above Fig.5 it is observed that the bending loss decreases as wavelength of light increases. It is found that the bending loss at 1310 nm wavelength of light is 0.06 dB/km and at 1550 nm wavelength of light is 0.029 dB/km respectively. Generally three types of losses were calculated when the optical fibers were designed [10]. These losses are scattering loss, bending loss and absorption loss. Other loss mechanism such as leaky mode loss, radiation induced loss, inherent defect loss, temperature dependent loss, core-cladding loss has negligible effect in the single-mode optical fiber [13]. In our simulation we have found that the total fiber loss at 1310 nm wavelength of light is 0.34 dB/km and at 1550 nm wavelength of light is 0.191 dB/km. We simulated equation (15) using to get chromatic dispersion. A plot of simulated result of chromatic dispersion of the fiber corresponding to different wavelength of light is shown in Fig.6. It is observed from Fig.6 that the chromatic dispersion increases as the wavelength of light increases. Chromatic dispersion becomes 18.2 ps/nm.km at 1550 nm wavelength of light. The chromatic dispersion in a single mode fiber is the sum of the material and waveguide dispersions. Since the material dispersion above 1300 nm wavelength of light becomes positive while the waveguide dispersion stays negative; the factor is that they cancel each other out, resulting in a zero chromatic dispersion. This occurs around at 1310 nm wavelength of light. For this reason chromatic dispersion is calculated at 1550 nm wavelength of light. The chromatic dispersion is the dominant dispersion mechanism in our designed single-mode optical fiber. Other dispersion mechanism such as intermodal dispersion is not present in the single mode fibers and we have assumed that the polarization mode dispersion has negligible effect in our designed single mode optical fiber.

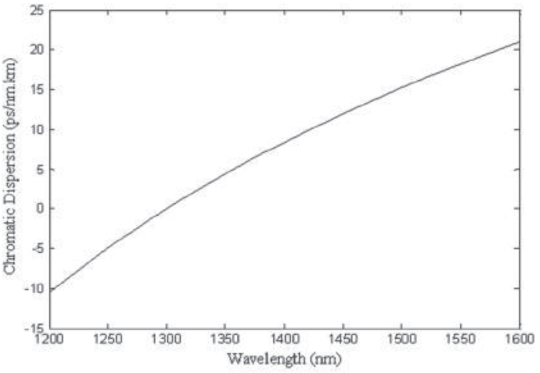

Fig.6. Chromatic dispersion (ps/nm.km) Vs Wavelength (dB/km)

The equations (19) and (20) were to find the bandwidth of our designed optical fiber. The simulation result shows that the bandwidth of our designed fiber is 13.7 Gbps. The simulation result shows that the parameters of our designed fiber are different from the existing fiber in the market given in [14]. This is because the optical properties of a fiber mainly depend on the material composition and the core cladding refractive index difference of the fiber. In our designed fiber we have considered that the core of the fiber material is ultra-pure low loss glass and negligible sensitive to hydroxyl ions. We also considered that the core-cladding refractive index difference is 0.00362. For this reason our designed single mode fiber exhibit better performance than existing single mode fiber in the market.

5. Comparison

The comparison between our designed fiber and typical commercially available fiber in the market [10] is given Table 1.

Table 1. Comparison between our designed fiber and commercially available fiber in the market.

Parameters	Our designed fiber	BF04445-01 SMT-1310B	BF04446 SMT-A1310H	BF04447 SMT-A1310J
Mode Field Diameter(μm)	9.47±0.63	93±0.5	93±0.5	93±0.5
Cladding Diameter(um)	125	125±2	125±2	125±2
Coating/Buffer Diameter(μm)	250	250±15	155±5	155±5
Coating Type	UV Acrylate	UV Acrylate	PYROCOAT™	Hermetic/ PYROCOAT™
Operating Temperature(ºC)	-40 to +85	-40 to +85	-65 to +300	-65 to +300
Operating Wavelength(nm)	1310/1550	1310/1550	1310/1550	1310/1550
Cut-off Wavelength(nm)	1300	1260±70	1260±70	1260±70
Numerical Aperture	0.12	0.11±0.02	0.11±0.02	0.11±0.02
Attenuation@1310nm(dB/km)	≤0.34	≤ 0.35	≤ 0.70	≤ 0.70
Attenuation@1550nm(dB/km)	≤0.191	≤ 0.25	≤ 0.60	≤ 0.60
Zero Dispersion wavelength(nm)	≤1300	1311±11	1311±11	1311±11
Zero Dispersion Slop(ps/[nm^2.km])	0.093	≤ 0.092	≤ 0.092	≤ 0.092

6. Conclusion

We have proposed a better design of single mode optical fiber that present the improved loss and dispersion performance and higher bandwidth. The simulated parameters show the suitability of designed fiber for long haul signal communication network with very high bit rate. We thus conclude that our designed fiber meets all requirements to be advantageous alternatives to classical step index single mode fiber.

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