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Simulation Study of Waveguide and Chromatic Dispersion of a Single Mode Step Index Optical Fiber

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ABSTRACT

An optical fiber is a superior medium of transmitting a signal from one end to the other end. It has the characteristics of long-distance transmission and large capacity to accommodate signal, but the dispersion in the fiber is one of the most important reasons for signal degradation. Dispersion depends on various parameters such as the operating wavelength, core radius, relative refractive index difference, source spectral width and length of the fiber link. We perform a simulation study of the waveguide and chromatic dispersion in a single mode step index optical fiber. The study has been done by using the simulation software "Understanding Fiber Optics on a PC". It has been found that pulse broadening due to waveguide dispersion decrease with increasing relative refractive index difference between core and cladding for 1310 nm of operating wavelength, 4.5 μm of core radius, 2 nm of spectral width and 50 ps of the input pulse width. It is observed that waveguide dispersion is negative in the single mode fiber region. On the other hand, chromatic dispersion becomes zero for the operating wavelength of 1310 nm, 4.5 μm of core radius, 2 nm of the spectral width, 50 ps of input pulse width and 0.20% of relative refractive index difference. For this zero chromatic dispersion, the optical pulse remains unchanged through a large distance of about 100 km of fiber length. This result will be an important consideration for designing of the good optical fiber.

Key words: Optical Fiber, Material Dispersion, Waveguide Dispersion, Chromatic Dispersion.

INTRODUCTION

An optical fiber is a transparent cylindrical filament of glass or polymer. It consists of a highly refractive index of the core surrounded by a lower refractive index of the cladding. Usually, the cladding is not necessary for light to propagate along the core of the fiber. It serves several purposes [1]. It adds mechanical strength and protects the core from surface contaminants. Light propagates longitudinally into the core following the total internal reflection law. A general communication system of the fiber comprises of an optical transmitter, transmission medium and a receiver [2]. The most important advantages of optical fiber as compared to electrical copper wire are transmission loss, very high bandwidth (BW), smaller size and much lighter in weight [3]. After a long research, optical fiber experiences a very little power loss. In 1970, the first optical fiber was produced with attenuation at 20 but now the attenuation has reached at 0.18[4]. In 1981, General Electric produced fused quartz ingots that could be drawn into strands 25 miles (40 km) long.

Due to the need to send data at higher capacities over longer distances grew over time, fiber optic professionals developed specific wavelength windows. These wavelength windows were confined to the 1310 nm and 1550 nm regions to prevent high degrees of attenuation and return loss. Although this appeared to be the simple solution to successful data transmission, limitations due to dispersion began to occur as networks advanced. As the need arose to send information over longer and longer distances, the fiber optic community developed additional losses that are become impossible to overcome. That means the fiber may loss the transmitting signal on its way and as a result the output signal at the receiver end of the fiber will be less than that of the original signal. Therefore though optical fiber is widely used for transferring the signal over long distances, it has many chances to attenuate the transmitting light signal [5].

The most important dispersion in SMSIF is the chromatic dispersion. It is also called the total dispersion of the fiber. It refers to the spreading of the light pulse at the receiver end due to the inherent wavelength dependency. Different spectral components of wavelength travel at different velocities within any medium (i.e., fiber) and reach the receiver end at different times. So the output pulse gets spread due to the dispersive nature of the material of the medium. Waveguide dispersion is another one that occurs in single mode optical fiber. Even if the fiber material has no any dispersive properties, waveguide dispersion can also occur. It merely occurs due to restricting the light within a certain region and is relatively small in single mode fibers. The main problem to reduce these losses is that optical fiber is very sensitive to its parameters change. When someone changes one parameter value of optical fiber during its fabrication process to reduce some types of loss then the other type of problem will appear. It is very difficult to reduce this type of loss by using only analytical techniques. In these cases it is important using computer-aided techniques, like simulation, to study the performance of the optical fiber.

We perform "Simulation Study of Waveguide and chromatic dispersion of a Single-Mode Step-Index Optical Fiber". The present study has been done using the simulation software "Understanding Fiber Optics on a PC". We use the software through the study and prepare the data tables and graphical representations. We work on SMSIF because it is the best road of communication for minimum dispersion [6]. The present study shows that waveguide dispersion is always a negative sign for single mode optical fiber. It increases with increasing relative refractive index difference for an operating wavelength of 1310 nm, 4.5 μm of core radius, 2 nm of spectral width and 50 ps of input pulse width. By using these parameters, chromatic dispersion becomes zero for which the relative refractive index difference is 0.20%.

2. MATERIALS AND METHODS

We use the software GST of "Understanding Fiber Optics on a PC" for this work [7]. The software is designed to give the reader a numerical appreciation and also graphical representations of the characteristics of the fiber. It allows the user to interactively change the parameters of to create the examples and also provides a platform to perform a simple calculation based mainly on single mode step index fiber. The parameters that are given in the software are wavelength of light, the refractive index of the core (n_1) and cladding (n_2), the radius of the core (a), relative refractive index difference (Δ), acceptance angle (i_m), spectral width, and fiber length etc. By changing the value of these parameters we can get different configurations of fiber every time. Then by analyzing these configurations we can set up suitable parameters for fiber and construct a good fiber with low dispersion. When all significant parameters for optical fiber and light transmission are given to the computer, the computer can simulate them according to the requirements.

For the present study, we consider some important parameters that are kept in constant for all graphical representation of optical fiber. One of the more confusing parameters to many is wavelength. For fiber optics with glass fibers, light in the infrared region's is used which has the wavelength longer than visible light, typically around 850, 1300 and 1550 nm. Single mode fibers usually operate in the 1310 nm or 1550 nm regions, where the attenuation is lowest. The wavelength of 1310 nm has been chosen for the present study because of the lower the wavelength, the less expensive the optics [8].

For the present study, fused silica glass has been chosen of the material of core because of its high purity and excellent transmission characteristics in a wide range of wavelengths. It is a type of glass containing very high chemical resistance and heat resistance. It is mainly composed of Si02 whose refractive index is 1.458. In fact, fused silica is the key starting material for optical fiber.

Single mode fibers have a very thin core diameter of about 10 μm [3]. For standard single mode fiber with 1310 nm of operating wavelength, 9 μm of core diameter is used. So for our present study, we work with the core radius of 4.5 μm. Another important parameter of the fiber is the normalized frequency (V) which represents the propagation path of the optical waveguide. For single-mode fiber, the typical V-values are always less than 2.405. In the present study, we always work with the V- number and keep its value around 2.405. Acceptance angle is also essential for signal transmission through the optical fiber. The higher value of i_m allows most light to propagate through the fiber. Further, the greater inclination of the optical waveguide to the fiber axis travel faster and produce lower pulse broadening at the output end of the fiber.

Refractive indices of core- clad are one of the most important parameters of the optical fiber. The propagation of light mostly depends on this parameter. During manufacturing processes, a small change of refractive index can cause fiber attenuation. So in order to reduce bend loss, we should emphasize the refractive indices of the fiber. The fractional difference (Δ) between the refractive indices of the core - cladding is known as the fractional refractive index change or relative refractive index difference. It is expressed as

$$\Delta = \frac{n_1 - n_2}{n_1}$$

This parameter is always positive because n_1 must be greater than n_2 [9]. When the refractive index of cladding increases with constant refractive index of core, refractive index differences decreases and hence V- number also decreases.

Acceptance angle (i_m) is the maximum angle that a ray can have relative to the fiber axis and propagate down the fiber. Higher value of i_m allows most of light to propagate along the fiber. For SMF, the larger the acceptance angle, more the fiber will be bent. It is written as

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$$i_m = \frac{1}{\sin\sqrt{(n_1^2 - n_2^2)}}$$

Fiber dispersion results in optical pulse broadening. The dispersion of a fiber depends on its length. A longer fiber causes more pulse broadening and it has a large dispersion.

In order to appreciate the reasons for the different amounts of pulse broadening within the various types of optical fiber, it is necessary to consider the dispersive mechanisms involved. These are classified as follow

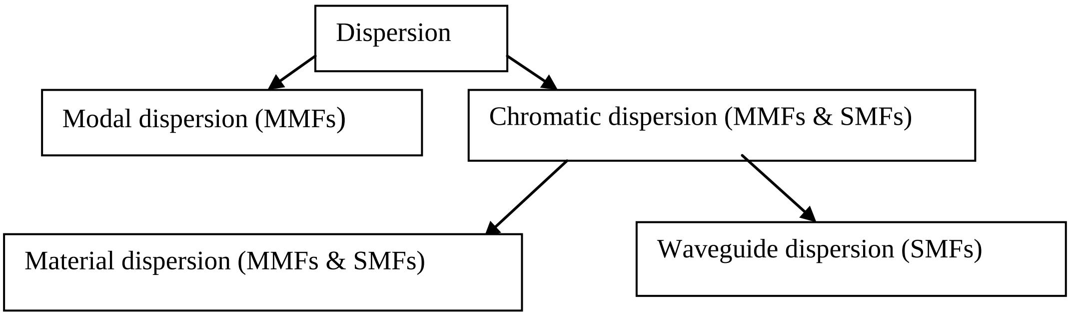

Figure 1: Different types of dispersion in optical fiber

In the Figure 1, we see that modal dispersion is significant only in MMF due to a large number of modes where chromatic dispersion is obtained for MMF and SMF. Also, we see that for SMF, chromatic dispersion is the sum of waveguide and material dispersion where waveguide dispersion is important only in SMF.

Material dispersion is the result of the finite line width of the light source and the dependence of the refractive index of the material on wavelength. It implies that the light in the fiber consists of a group of wavelengths. Light waves of different wavelength travel at different speeds in a medium (i.e., silica fiber). Consequently, the light tends to broaden as they travel down the fiber. This is known as material dispersion. It is observed that material dispersion tends to be very low in the longer wavelength region around the second optical window. It is also observed that material dispersion above 1300 nm wavelength of light becomes positive [10]. For any single wavelength of light, material dispersion is fixed.

Waveguide dispersion is mainly caused by the refractive indices of the core and cladding of an optical fiber. For this reasons, regardless of the nature of the light source and optical fiber, some light travels in the cladding, as well as of the core causing pulse broadening. In other words, we can say that light energy travels at slightly different velocities in the core and cladding because of the slightly different indices and reach the end face at different times causing pulse broadening. Ignoring the wavelength dependence of the core and cladding refractive indices and assuming that $\Delta \ll 1$, by simple manipulations the contribution due to waveguide dispersion only we can write as [3]

$$\Delta\tau_w \cong -\frac{n_2\Delta}{0.0003\lambda} V \frac{d^2(Vb)}{dV^2}$$

where λ is in μm. Under the weakly guiding approximation, b (V) is a function of V. From the above Eq. we see that waveguide dispersion depends on the fiber geometry such as refractive index of cladding (n_2), relative refractive index difference (Δ) and V-number etc. Therefore by controlling the fiber parameters, it is possible to optimize the pulse broadening due to waveguide dispersion.

The waveguide dispersion can also be expressed in terms of the wavelength variation of the Petermann-2 spot size ($\overline{W}$), as [3]

$$\Delta\tau_w \cong -\frac{1}{0.0024\pi^2 n_2{}^2} \lambda \frac{d}{d\lambda}\left(\frac{\lambda}{\overline{W}^2}\right) ps/km-nm$$

where $\overline{W}$ is the second spot size, known as the Petermann-2 spot size and related to the loss due to waveguide dispersion. The wavelength variation of this spot size for a given fiber can be measured experimentally and hence, the waveguide dispersion of a fiber can be estimated. From this equation it is observed that for a lower value of Petermann-2 spot size ($\overline{W}$), narrower pulse spread will be obtained. In such a case, a pulse will broaden by the following imperial formula due to waveguide dispersion which is defined as follows

$$\tau_0 = \Delta\tau_w \times \mathrm{L} \times \Delta\lambda$$

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Chromatic dispersion is about the different time delay between the various wavelengths contained in a light pulse. Therefore chromatic dispersion is an important property which causes different wavelength of light travels to different speed [11]. Longer wavelength of the wave travels faster than the lower wavelength of the wave, thus they reach the destination in a different time. Therefore for an initial narrow input pulse, a combination of different time delay results from a wide output pulse. Chromatic dispersion is popularly known as intramodal dispersion. It contributes from two dispersions: material dispersion and waveguide dispersion. Thus, the total dispersion can be written as

$$\Delta\tau_{ch} = -\frac{1}{0.0003\lambda}(\lambda^2 \frac{d^2 n_e}{d\lambda^2}) ps/km - nm.$$

The above Eq. has contributions from both material and waveguide dispersion where λ is in µm. This equation can be written as

$$\Delta\tau_{ch} = -\frac{\lambda}{c}\frac{d^2 n_e}{d\lambda^2} ps/km - nm$$

where c is the speed of light in vacuum and n_e is a function of wavelength and the material dispersion.

Therefore,

$$n_e = \beta(\lambda, n_m(\lambda))/k_0$$

where β is the propagation constant and $k_0 = 2\pi/\lambda$ is the wave number in free space and n_m (λ) is the refractive index of fiber material which can be estimated by using Selemeiers formula. Hence the pulse broadening is given by

$$\tau_0 = \Delta\tau_{ch} \times \text{L} \times \Delta\lambda$$

Also since chromatic dispersion is a combination of material and waveguide dispersion, we can write that

$$\Delta\tau_{ch} = \Delta\tau_m + \Delta\tau_w$$

where $\Delta\tau_m$ and $\Delta\tau_w$ represent the material dispersion and the waveguide dispersion respectively. Since we have already seen that material dispersion is fixed and waveguide dispersion is changeable depending on fiber structure, therefore careful design at fiber materials and index profiles, the single mode fiber will have a zero chromatic dispersion with no change of output pulse at the receiver end.

Above all, the present simulation work has been done under the consideration of the following parameters:

- Working with 1310 nm of operating wavelength of light to find out minimum dispersion and for long optical fiber path.
- The radius of the core should be consisted in 1-5 µm and also the V- number should be less than or equal to 2.405.
- The values of the spot size ($\overline{W}$) should be kept in small to reduce the pulse broadening.
- Working with small spectral width of the light source because smaller the spectral width, narrower will be the shape of the light spot.
- Acceptance angle must be larger because larger the acceptance angle, more the light will be confined into the core.

3. RESULTS AND DISCUSSIONS

For a long distance communication, longer lengths of fiber may be required and so there is a big chance for the light pulse to get broadens. Waveguide dispersion is the most significant for pulse broadening in SMSIF. For the present simulation-based study of the waveguide and chromatic dispersion we work with some parameters of an optical fiber and in every case, we have fixed the wavelength (λ) of 1310 nm because of its lower material dispersion as compared to others. Also, we have fixed the core radius of 4.5 µm because below this value light pulse gets broaden largely, the spectral width of 2 nm for laser source because narrow spectral width produces pure light output by reducing the pulse broadening and 50 ps of the input pulse width. Fused silica glass has been considered as the material of core whose refractive index is 1.458. In every case, we have increased the relative refractive index difference between core and cladding that means decrease the refractive index of the cladding. Then we have measured the waveguide dispersion and the corresponding output pulse in terms of the prolonged fiber length by the simulation software.

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Table 1: Results of waveguide dispersion and output pulse width for different relative index differences

λ (nm)	*a* (μm)	n_1	Input pulse width τ_0 (ps)	L (km)	Δ (%)	$\Delta\tau_w$ (ps/km-nm)	Output pulse width τ_0 (ps)
1310	4.5	1.458	50	100	0.16	-4.1	828
					0.18	-3.9	772
					0.20	-3.6	712
					0.22	-3.2	650

From the above Tab.1 it is observed that the waveguide dispersion increase with increasing relative index difference between core and cladding. It is also observed that the waveguide dispersion is always a negative sign in the single mode fiber region. The graphical representation between the shape of the output pulse and the fiber length of the simulation results is shown in the following Fig.1.

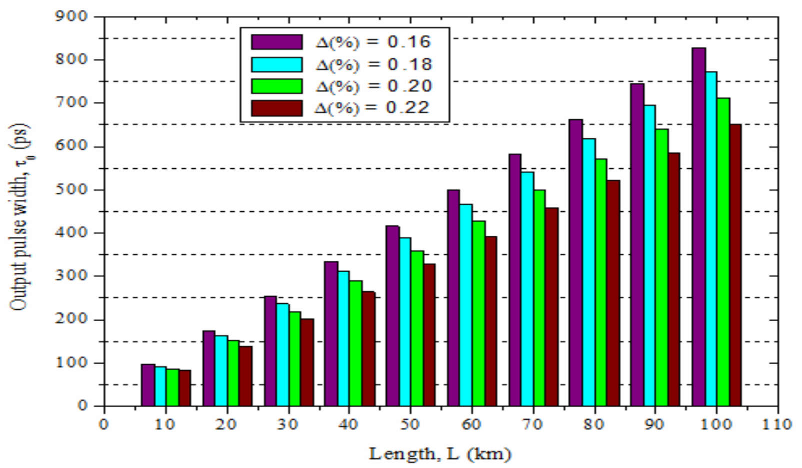

Figure 2: Variation of output pulse width with length for different relative index differences

From the Figure 2 it is observed that for lower value of relative refractive index difference (0.16%), the shape of the output pulse becomes broaden. Alternatively with increasing relative index difference, the shape of the output pulse starts to become narrower for a particular fiber length.

Usually chromatic dispersion contributes from the material and waveguide dispersion for SMSIF. We have already seen that waveguide dispersion can be changed and it is always negative sign in single mode optical fiber. In the contrast, from the theory, we know that material dispersion cannot be changed and so it is always fixed for a particular wavelength. Therefore for specific fiber parameters, if waveguide and material dispersion are exactly of opposite signs, then they cancel each other's effect and produce zero chromatic dispersion. Therefore we can find zero dispersion for suitable fiber parameters.

By using the selected fiber parameters of the analysis of waveguide dispersion, we have also measured the chromatic dispersion or total dispersion. Here the simulation result of the chromatic dispersion and the shape of the output pulse in terms of fiber length are shown in the following Table 2.

Table 2: Results of chromatic dispersion and output pulse width for different relative index differences

λ (nm)	a (μm)	n_1	Input pulse width τ_0 (ps)	L (km)	Δ (%)	$\Delta\tau_{ch}$ (ps/km-nm)	Output pulse width τ_0 (ps)
1310	4.5	1.458	50	100	0.16	-0.6	121
					0.18	-0.3	74
					0.20	0	50
					0.22	0.3	84

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From the Table 2 it is observed that the chromatic dispersion increases with increasing relative index difference between core and cladding. We see that below 0.20% of relative index difference, chromatic dispersion is negative. Therefore light pulse travels slower and gets broaden. On the other hand, above of 0.20%, chromatic dispersion is positive and also gets broaden. For 0.20%, chromatic dispersion passes through zero dispersion. Therefore in a single mode step index optical fiber operating with 1310 nm of wavelength, 4.5 µm of core radius, 2 nm of spectral width and 0.20% of refractive index difference, the chromatic dispersion is zero and thereby dominates the negative effect of the waveguide dispersion and the positive effect of the material dispersion. The variation of the shape of output pulse with fiber length is shown in the Fig.2.

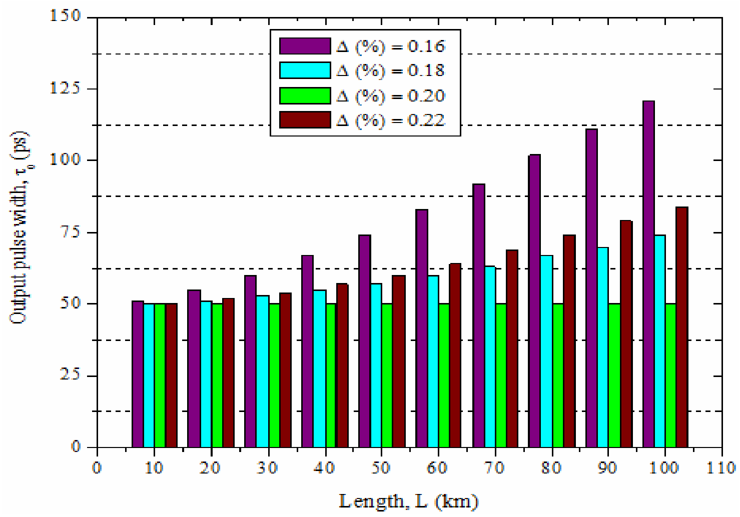

Figure 3: Variation of output pulse width with length due to the chromatic dispersion

From the Figure 3 we see that for the smaller value of relative index difference, the shape of the output pulse becomes wider. However it is narrower with increasing relative index difference. From this Figure it is also observed that the optical signal width becomes same as the input signal width over a large distance of 100 km for Δ = 0.20% and a = 4.5 µm.

4. CONCLUSION

Signal degradation is one of the most important properties of the optical fiber and it is the key distance limiting parameters in optical fiber transmission. Dispersion is one of the reasons of signal degradation that results in pulse broadening over long distance fiber link by limiting power bandwidth. In this circumstance the present work is to reduce the pulse broadening due to waveguide and chromatic dispersion in a single mode step index optical fiber. The work has been done by using simulation software "Understanding Fiber Optics on a PC" for SMSIF. The present study shows that for 1310 nm of operating wavelength, 4.5 µm of core radius, 2 nm of spectral width and 50 ps of input pulse width, the waveguide dispersion increases with increasing the relative index difference between core and cladding and always negative sign in the single mode fiber region. Also for prolonged fiber length, the shape of the output pulse width becomes narrower with increasing relative index difference due to waveguide dispersion.

Since material dispersion is fixed, so by changing the waveguide dispersion and balancing it against material dispersion, the dispersion characteristics of the fiber can be engineered to required values over the preferred operating fiber parameters. From the present study it is shown that for 1310 nm of operating wavelength, 4.5 µm of core radius, 2 nm of spectral source width with 0.20% of relative index difference between core and cladding, chromatic dispersion becomes zero. It is also observed that for such parameters with input pulse width of 50 ps, the shape of the output pulse remains unchanged over 100 km of fiber length. Therefore for this data set, chromatic dispersion dominates the negative effect of waveguide dispersion and also the pulse broadening due to waveguide dispersion.

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