

EXPERIMENTAL CHARACTERIZATION OF FIBER OPTIC COMMUNICATION LINK FOR DIGITAL TRANSMISSION SYSTEM

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Abstract

In this paper, main focus is on the experimental characteristic of optical communication link and of their components. We give an introduction to optical fiber systems and various phenomena related to it. The phenomena of attenuation and dispersion are discussed elaborately and details are provided through experimental observation and verification. A laser diode and photodetector are also discussed and their characteristics curves are plotted. All the details about various topics mentioned above are concluded and verified through experiments.

Keywords:

Attenuation, Dispersion, Source, Detector

1. INTRODUCTION

An optical fiber is a cylindrical structure made from a transparent material such as glass and consists of a central core of refractive index n_1 , surrounded by a cladding of refractive index n_2 . Light gets guided through the fiber by total internal reflection, in which a light ray incident on an interface between the denser medium (a medium of higher refractive index) and a rarer medium (a medium of lower refractive index) at angles greater than the critical angle, gets totally reflected, i.e. undergoes complete reflection [1]-[2]. The realization of low loss optical fibers and room temperature operation of compact semiconductor lasers in 1970, laid the foundation for long distance fiber optic communication. Technological advances such as optical amplifiers, dispersion compensators, high speed transmitters and receivers, optical dense wavelength division multiplexing etc. have contributed to the phenomenal growth of optical fiber communication industry [3]. The increased demand on the bandwidth continues and new innovations such as photonic crystal fibers, tunable lasers, high speed modulators, all optical signal processing, compact integrated optical devices, new modulation formats etc are expected to cater to this need [4].

This paper presents, complete experimental characterization of optical fiber communication system with emphasis a laser diode characteristics, attenuation, dispersion and, photo detector etc. In section 2 about Light Runner kit is discussed. Experiments of attenuation and dispersion in optical fiber are performed in section 3 and 4 respectively. Experiments of characterization of laser diode and photo detector are performed on Light Runner in section 5 and 6 respectively. Finally, conclusion of the paper is presented in section 7.

2. ABOUT LIGHT RUNNER

The Fig.1 shows the Light Runner kit. In order to exploit the full potential of fiber optic communication, exposure of faculty and students in academic institutions as well as scientists and engineers in R&D institutions and industries, to experimentation

in fiber optics has become an absolute necessity. Towards this end, several Fiber Optic Training (FOT) kits have been developed. However, the FOT kits available currently in market primarily deal with single wavelength measurements and demonstrate basic communication principles [5]. However we can analyze 4-channel WDM, transmission system by using a proposed kit.



Fig.1. Light Runner kit

Light Runner enables the user to perform experiments regarding Fiber Characteristics, Component Characteristics, Optical Communication Systems and Testing and Analysis.

2.1 EXPERIMENT OF ATTENUATION IN OPTICAL FIBER

Intrinsically, the loss can take place because of absorption. But stronger loss inside the optical fiber is called as a scattering loss. During the manufacture of optical fiber, there are very small micro-center of little difference refractive index, then the average value. In other words, some different type of micro region distributed all through the region. Therefore, as light tries to traverse through the optical fiber, it seems small perturbation through the refractive index. Fig.2 shows the phenomenon of scattering. This phenomena is very similar to the wave signal tries to pass through the environment having rain drops and signal scatters. So, due to these micro-structures inside the optical fiber takes place and these scattering is called the Rayleigh scattering. For a sustain guiding of light, the light must be confined within the numerical aperture. Any light scattering outside the numerical aperture cone will not be guided by the optical fiber and will be lost from the side walls of the optical fiber [6].

This is known as scattering loss and Rayleigh scattering is very strong function of wavelength. The Rayleigh scattering goes as λ^{-4} . For every doubling of wavelength, the Rayleigh scattering loss is reduced by the factor of 1/16. Now primary

discussion is that 1550 nm wavelength shows low loss, compare to 800 nm. So, this shows the substantial reduction in the Rayleigh scattering.

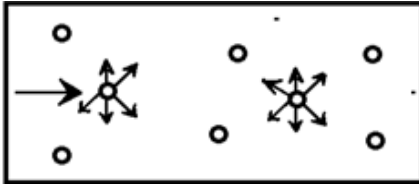


Fig.2. Phenomenon of scattering

The Glass is a very bad conductor of infrared. So, all the infrared are very rapidly attenuated. Longer the wavelength, loss increases very rapidly. As we increases the wavelength, the Rayleigh scattering loss increases but at the same time for the higher wavelength the infrared absorption loss starts dominating. There is also an impurity called OH^- molecules which normally water molecules. Even if we purify the glass with a high accuracy, if it is exposed in the environment typically the water molecules get the places inside the glass molecules. These molecules cannot be completely removed from the glass. Water molecules gives the absorption exactly lies in the valley. Due to the OH^- loss the optical fiber attenuation window splits into two parts.

We are talking about the loss due to the intrinsic characteristics of the optical fiber. As soon as the optical fiber is made, we can face the loss due to scattering and absorption. But in addition to these losses when any optical fiber is established inside the system, some losses take place due to environment and improper handling of the optical fiber. Absorption and scattering loss may take place even in the ideal, before laying the fiber inside the system. If we place the fiber inside the system, due to the improper placement of optical fiber, the fiber may deform in the micro scale region.

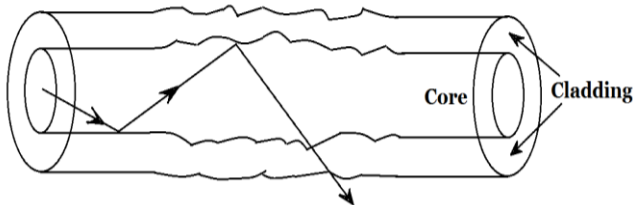


Fig.3. Phenomenon of micro bending loss

Ideally the walls of the core and cladding should be straight, but because of some pressure by external environment the side walls of the optical fiber may get deform. Fig.3 shows the phenomenon of micro bending loss. Even if we touch the fiber, that pressure is enough to create the deformation in the micro-level. If the side walls of the optical fiber are purely straight and plane, then light can travel by the multiple reflection. But if the side walls of the optical fiber are deform, then normal changes occurs and it cannot satisfy the critical angle condition and simply energy leaks out. Due to the presence of micro bending small portion of light energy leaks out from the fiber and this is called the micro-bending loss [6].

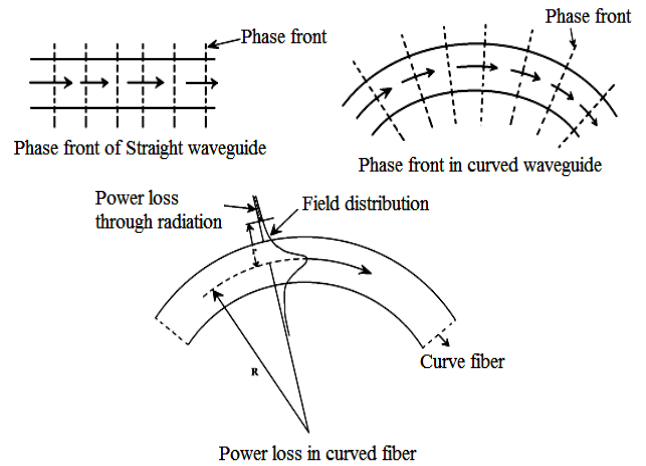


Fig.4. Phenomenon of macro-bending loss

Another type of loss takes place inside the optical fiber known as the radiation loss. Fig.4 shows the phenomenon of macro-bending loss. If the fiber is gently bend over a large arc and the radius of arc is much larger compare to the wavelength, then leakage of energy takes place and that is called as the radiation loss. Actually, if the light passes through the straight line inside the optical fiber, then its phase front remains perpendicular to the surface of the optical fiber. Hence, when the energy travels inside the optical fiber then every point in the phase front moves with the same speed. Now, if the fiber is gently bent, then phase front becomes an arc. Again the phase front will be perpendicular to the direction of propagation, but now the direction of propagation is an arc. Now the phase front will not be parallel to each other, but it will try to meet at the center of curvature of the arc. In this case the phase front moves like a fan which are pivoted to center of curvature of arc. Now, when this happen every point on the wave does not move with the same speed. Because, as we go towards the center of curvature of the arc the velocity decreases and as we go away from the center of curvature the velocity increases.

Now, at a particular distance a situation comes, where the velocity acquires the velocity of light intrinsically and beyond that velocity cannot be increased. As a result, the energy, which is beyond that distance, cannot propagate with these phase front. They slowly detached and leaking from the structure. This loss is called as the macro-bending loss or scattering loss. The important point to be note here is no matter how gentle is the tilt of optical fiber, we can have always distance at which the velocity of wave become equal to the speed light in that medium and energy will lost. The loss in an optical fiber is measured in logarithmic units of decibels per kilometer (dB/km) and is defined by the following equation,

$$\alpha(\text{dB/km}) = -\frac{10}{L} \log \left(\frac{P(L)}{P(0)} \right) \quad (1)$$

$$\text{Attenuation in dB} = -10 \log (P_2/P_1) \quad (2)$$

where, $P(0)$ is optical power at the input ($z = 0$) and $P(L)$ is optical power at the output i.e. L km away from the input ends. Here we assume z to be the direction along the length of the optical fiber.

Thus if we assume that the optical power at the entrance phase of the optical fiber is 1 mW and after a distance of 10 km the measured power is 0.1 mW, then the loss coefficient of the fiber will be 1dB/km. If light propagate in the same fiber over a distance of 30 km, then the loss suffered will be 30 dB. Using Eq.(1) we can calculate the output power of the end of the 30 km as 1 μ W.

Attenuation is a very important property of any optical fiber and it decides the maximum distance that the light wave can propagate and still be detectable at the output of the receiver. Attenuation is a function of wavelength and the minimum attenuation of silica optical fibers occurs at a wavelength of 1550 nm. Typical optical fiber loss is found to be in the range of 0.20 to 0.30 dB/km at 1550 nm and therefore even after propagating through 80 km of such a fiber, the output will be 1% of the input power. Fig.5 shows the experimental setup with waveform of the input signal.

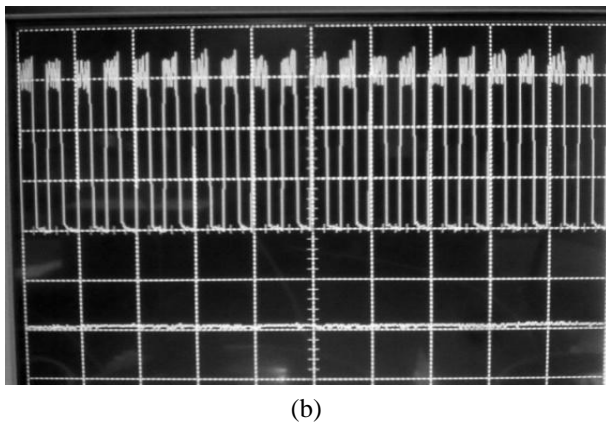
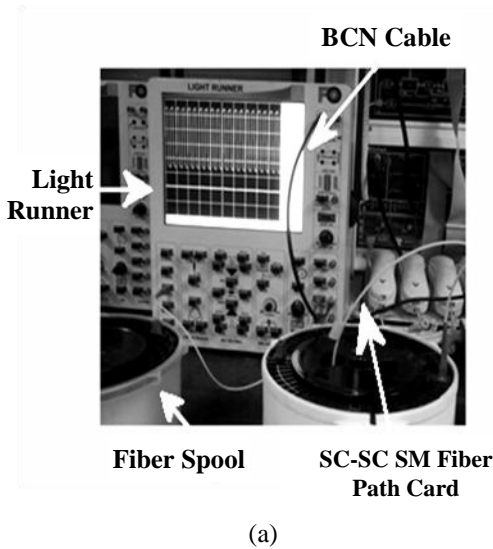


Fig.5. Experimental setup for attenuation experiment (a) waveform of the input signal, (b) waveform at the output of fiber end after attenuation

The value of power loss in decibels (dB) is calculated according to the Eq.(1). A graph between power loss (dB) and length (Km) is plotted.

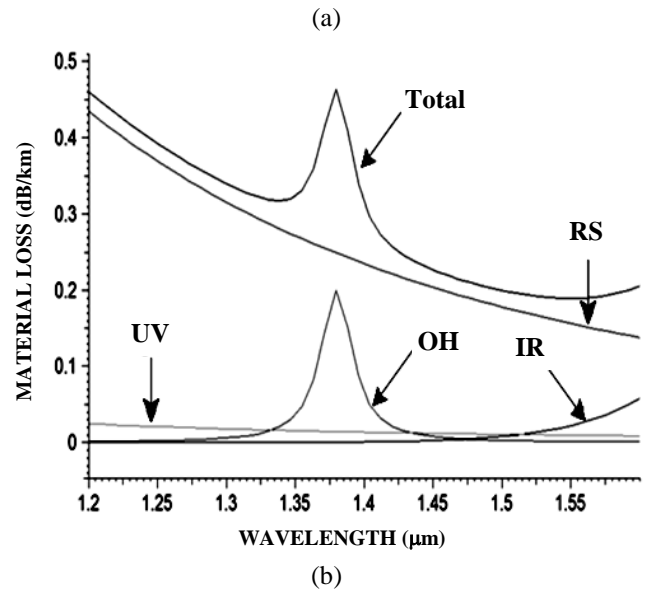
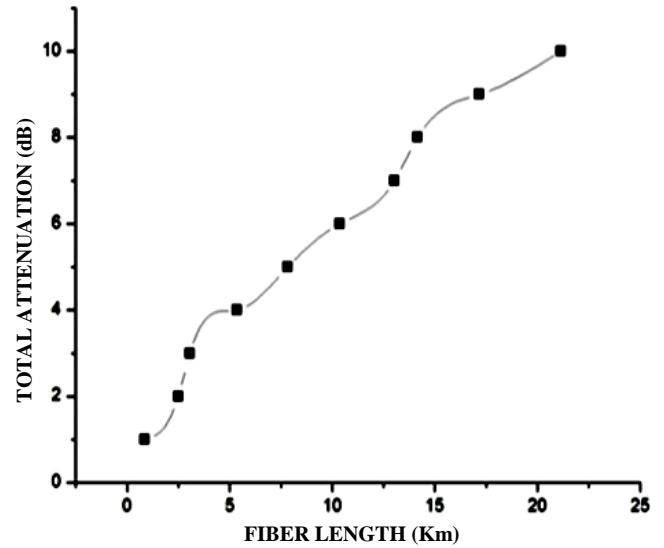


Fig.6. (a) Experimental Plot of power loss vs. fiber length (b) different material loss vs. wavelength

From Fig.6(a), it can be seen that the power loss goes on increasing with the increase in length. At fiber length 3km the loss is minimum, thus the attenuation coefficient is also minimum. It can be concluded from this experiment that the loss as well as attenuation coefficient both increase with increase in length of the fiber.

The Fig.6(b) shows the plot of different material loss vs. wavelength. In this case, we consider the loss due to OH, Infrared, UV light and Rayleigh scattering. Fig.7 shows the effect of micro bending and macro-bending with respect to wavelength. From this plot, it seems that macro-bending is small than the micro-bending and both are gradually increasing with wavelength.

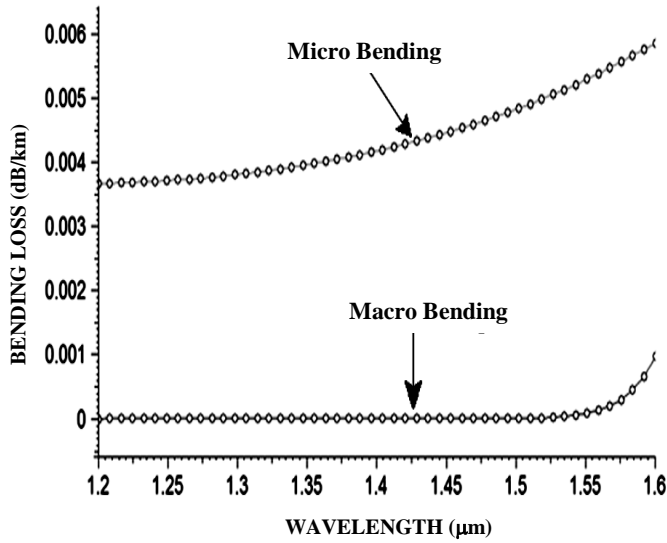


Fig.7. Experimental observation of micro bending and macro-bending with respect to wavelength

2.2 EXPERIMENT OF DISPERSION IN OPTICAL FIBER

If we put a pulse of energy inside the optical fiber, the pulse energy travels in the different path in the form of different rays. As a result the rays do not reach at the other end in the same time. Due to this the pulse broadening phenomena takes place. This phenomena is called as the Dispersion because the multipath inside the optical fiber. If we take single mode fiber, then these phenomena will not take place. In general, we have three types of dispersion take place. Intermodal dispersion takes place in a multimode fiber. But, if we take single mode optical fiber, then two types dispersion takes place (i) Material Dispersion (ii) Intra-modal dispersion [6-7].

If we send the signal in the form of pulses through the optical fiber, the pulse gets broaden. Here we are not saying that this pulse shape retained or anything. Actually these pulses represent the presence or absence of bits. Hence as the distance becomes more and more, the pulse gets broaden more and more. Initially, pulses are clearly identified, when we travel small distance the pulses partly overlap and furthermore they start merging into each other or they start losing their identity. Essentially, the pulse broadening phenomena puts the restriction over the distance at which we can send the signal, so that they can be recovered. The Fig.8 shows the pulse broadening phenomenon in optical fiber.

Pulse broadening intrinsically related to carrier bandwidth. More carrier bandwidth more will be pulse broadening [8]. Also pulse broadening is directly proportional to the traveled distance. As we know that group velocity is given by,

$$v_g = \frac{\partial \omega}{\partial \beta} = 2\pi c \frac{\partial(1/\lambda)}{\partial \beta}$$

$$\text{Group delay per unit length } t_g = \frac{l}{v_g}$$

$$\text{Pulse broadening } \tau_g = \frac{dt_g}{d\lambda} \sigma_\lambda$$

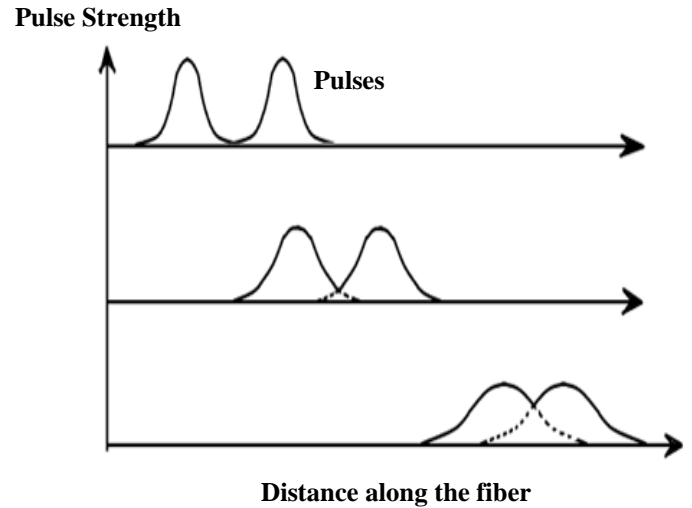


Fig.8. Pulse broadening phenomenon in optical fiber

Hence, we can say that pulse broadening per unit length for unit spectral width is called Dispersion. A dispersion phenomenon is a weak phenomenon. Each dispersion can be calculated independent of each other. When we calculate the material dispersion, we assume that waveguide dispersion is negligibly small. When we go for intra-modal dispersion, then we assume that material dispersion is practically small. The total dispersion is just the addition of all other dispersion.

2.2.1 Material Dispersion:

In case of material dispersion, the refractive index is function of wavelength but there is no guiding of light inside the fiber. We can write the phase constant as

$$\beta = \frac{2\pi}{\lambda} n(\lambda).$$

So phase constant varies with respect to λ

$$t_g = \frac{d\beta}{d\omega} = \frac{d\beta}{d\lambda} \frac{d\lambda}{d\omega}.$$

$$\text{But } \omega = \frac{2\pi c}{\lambda}$$

$$t_g = -\frac{\lambda}{c} \frac{dn(\lambda)}{d\lambda}.$$

Hence, we can write the material dispersion as

$$D_{mat} = \frac{dt_g}{d\lambda} = -\frac{\lambda}{c} \frac{d^2n(\lambda)}{d\lambda^2}.$$

2.2.2 Waveguide Dispersion:

Waveguide dispersion is the dispersion due to the modal nature inside the optical fiber. We have seen $b - V$ diagram where V is characteristics parameter proportional to the frequency. b is the normalized propagation constant, which is related to the phase constant of particular mode. Hence from the diagram we would like to find out, what will be the group velocity, and how it can vary as a function of the wavelength. As we have discussed that we will take one dispersion at a time. Now, when we investigate the waveguide dispersion, then at that time, we will assume that material dispersion is zero. The core-

cladding material is not having the intrinsic pulse broadening phenomena; the dispersion is taking place just because of guided nature [9-10]. Essentially we would like to find out the dispersion in terms of the parameters b and V . We can write,

$$b = \frac{\beta^2 - \beta_2^2}{\beta_1^2 - \beta_2^2}$$

where, β_1 and β_2 are the phase constant intrinsically for medium core and cladding. And β is the phase constant for the particular mode. We also know that for the proper communication the core and cladding refractive index are very close to each other. Thus for the practical fiber or in other words for weakly guiding fiber.

$$n_1 \approx n_2$$

We also know that when a mode propagates the phase constant is also bounded by β_1 and β_2 .

$$\beta_1 < \beta < \beta_2$$

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

Since, n_1 and n_2 is very close to each other the range of β is very small

$$b = \frac{\beta - \beta_2}{\beta_1 - \beta_2}$$

$$\beta = \beta_2 \left[1 + b \left\{ \frac{\beta_1 - \beta_2}{\beta_2} \right\} \right]$$

$$\beta = \beta_2 [1 + b \Delta]$$

Group delay

$$t_g = \frac{d\beta}{d\omega} = \frac{n_2}{c} \left[1 + \Delta \frac{d(bV)}{dV} \right]$$

where,

$$V = \frac{a\omega}{c} \sqrt{n_1^2 - n_2^2}$$

Hence, we can write the waveguide dispersion

$$D_{wg} = \frac{dt_g}{d\lambda} = -\frac{n_2^2 \Delta}{c\lambda} V \frac{d^2(bV)}{dV^2}$$

Total dispersion is the summation of the two dispersions. Both the dispersion because of the finite bandwidth. These dispersion are together is called the chromatic dispersion.

$$\text{Chromatic dispersion} = D_{mat} + D_{wg}$$

D_{mat} depends upon the material taken for the construction of the optical fiber. D_{wg} is the parameter that depends upon the structure of the fiber. It depends upon the fiber based parameters and it can be manipulated as a result the total dispersion quantity is manipulated. Fig.9(a) shows the experimentally observed value variation of group delay vs. wavelength; it seems from this plot that group delay is gradually increases with wavelength. Fig.9(b) shows the effect of wavelength on dispersion.

The Fig.10 shows the experimental setup along with the output waveform. Using the experiment it is possible to check if lower wavelengths travel slower or faster than longer wavelengths, whether the time difference increases linearly with increasing length of the fiber [11]. The Fig.11 shows the input waveform for

1550nm and 850nm laser source. The Table.1 shows the observations of delay between position of 850 nm and 1550 nm Laser pulses (ns) and dispersion with respect to fiber length.

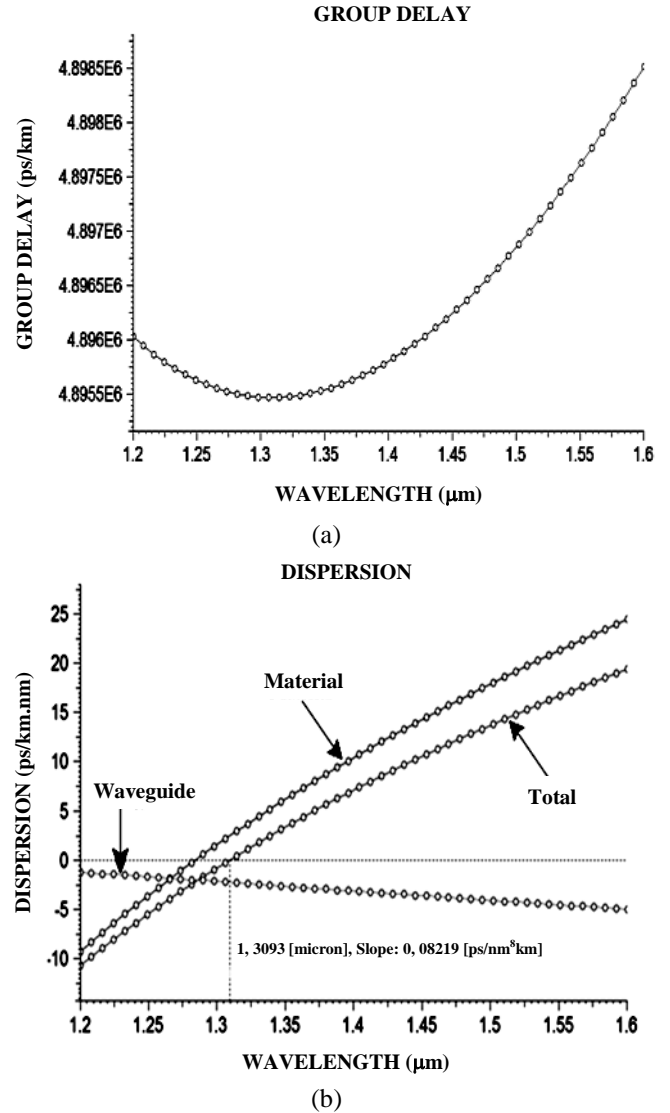


Fig.9. Experimental observation of (a) group delay vs. wavelength (b) dispersion vs. wavelength

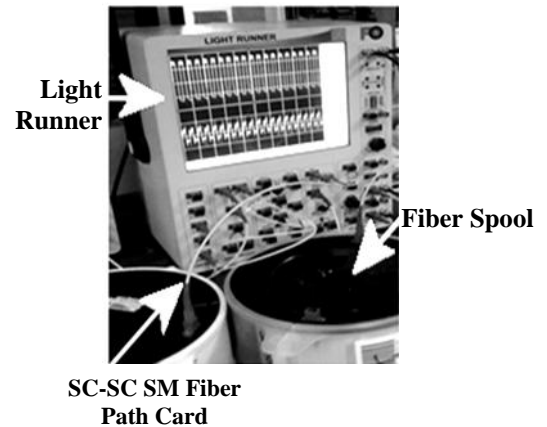


Fig.10. Experimental setup along with the output waveform

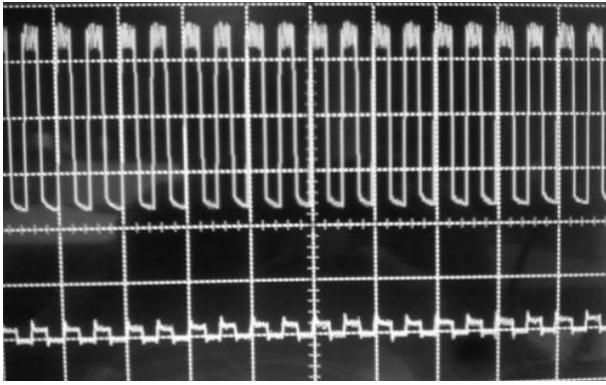


Fig.11. Input waveform for 1550 nm and 850 nm laser source

Table.1. Observation of dispersion with respect to fiber length

Fiber Length (km)	Position of 850 nm Laser Pulse (μ s)	Position of 1550 nm Laser Pulse (μ s)	Delay between position of 850 nm and 1550 nm Laser pulses (ns)	Dispersion per km
1.0	19.93	19.45	0.48	0.48
2.0	20.09	19.45	0.64	0.32
3.0	19.93	19.45	0.48	0.16
4.0	19.93	19.77	0.16	0.04
5.0	19.77	19.45	0.32	0.064
6.0	19.93	19.77	0.16	0.032
7.0	20.09	19.93	0.16	0.023
8.0	19.77	19.14	0.63	0.078

Average Dispersion per km = 0.149

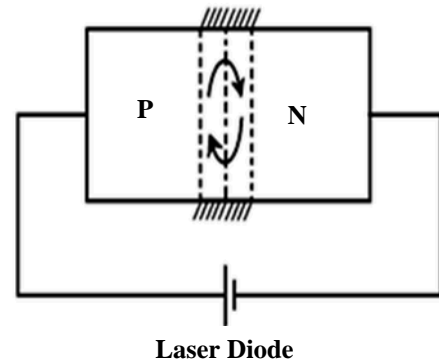
Dispersion from Selmeyer equation = 10 μ s

Due to dispersion, pulses of light launched at 850 nm and 1550 nm take different times and the time difference determined per km is consistent with the estimation obtained from the Selmeyer equation.

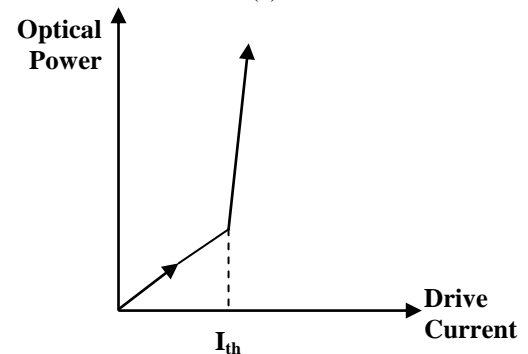
2.3 EXPERIMENT OF CHARACTERIZATION OF LASER DIODE

An optical source is one of the most important components of the optical communication link. Although there are abundant of light source in the universe. These sources are not very well suitable for optical communication. The reasons are very simple. Some sources are having very spectral width. Many of the sources cannot be used as an optical source in optical communication. Many of the sources cannot be switched on and off at very large rate [6]. As LED have larger spectral width and also it has very low efficiency. So, it cannot be used as a long distance communication. Inside LED we have P-N junction, and by making the P-N junction forward biased, the electrons and holes are injected in a common region, they recombine and then we are having the generation of light due to recombination. But, the photon generated can move in all possible direction. Hence, LED has extremely low conversion efficiency. So, we required to create some type of positive feedback mechanism inside the P-N junction. They will remain for the longer time inside P-N junction; they will create the stimulated emission and generate the directed beam of light inside the P-N junction. Fig.12(a)

shows the P-N junction laser diode and its mechanisms and Fig.12(b) shows the characteristics curve.



(a)



(b)

Fig.12. (a) P-N junction laser diode (b) characteristics curve

Schematically, we can take the P-N junction. Then, if we make a reflecting mechanism over the P-N junction, then photon will be trapped inside the region and stimulated radiation action will take place. In fact by making the fabrication of LED in such a way that we have some kind of reflecting boundary which will make the photon confine for longer time, the same LED can be converted into the laser.

The principle is that a proper P-N junction material with proper polishing so that photons can be trapped inside the material, for stimulated radiation action. A highly polished LED can acts as a Laser. This is the device that will be very compatible with the electronic circuit. Laser diode is widely used for the long distance communication. Initially, the efficiency was very small, electric current flows [12]. This provides the recombination between electrons and holes but most of the photon gets lost but there are linearity between the optical power and current flowing through the circuit. The same things happen along with the laser diode, because photons are confined. For some current we are having high optical power. Again the relationship between the optical power and currents are linear but the change in the optical power for small change in current are more in comparison to LED.

At low current stimulated emission still not overcome the losses inside the device. So, the device starts functioning like LED. So, for low current efficiency of device is very small. Once we reach to a certain value beyond which the stimulated emission overcomes the losses suddenly lasing action starts and we have large efficiency of the device. Even for the small

change in the current, we have the large change in the output. The laser diode has the typical characteristics that almost changes at threshold current.

LED can be easily used for the analog communication due to linear characteristics over a wide range. By changing the current we can get the same behavior in the optical signal. Whereas in case of the laser diode we have sudden break in its characteristics and it shows switching action. Hence, device is more suitable for the switching purpose. In both cases, we can see the linear variation, but characteristics are not very stable for the modulation as far as laser diode is concern. Hence, the laser diode is not suitable for the linear modulation, rather suitable for the switching types of action i.e., suitable for the digital modulation. Fig.13 shows the experimental setup for laser diode characteristics.

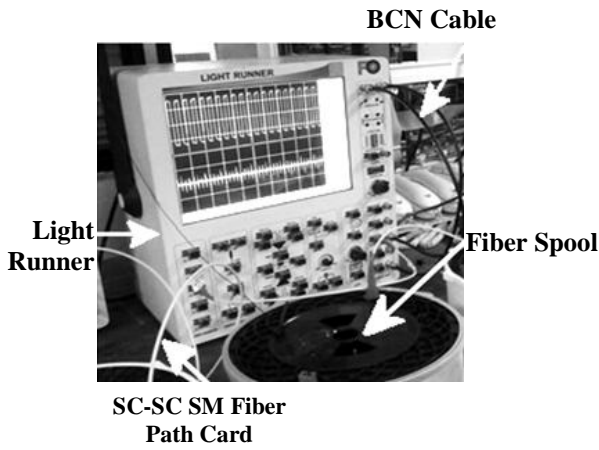


Fig.13. Experimental setup for laser diode characteristics

The Fig.14(a) shows the plot of diode current with respect to laser optical power. From the measurement it is found that the threshold current is 5.7mA, the optical power of the laser is linear with respect to its forward current and the monitor diode current is directly proportional to the laser power.

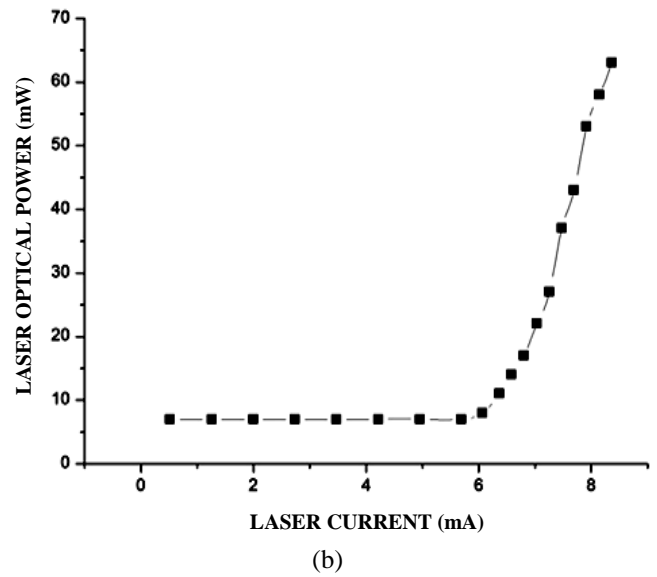
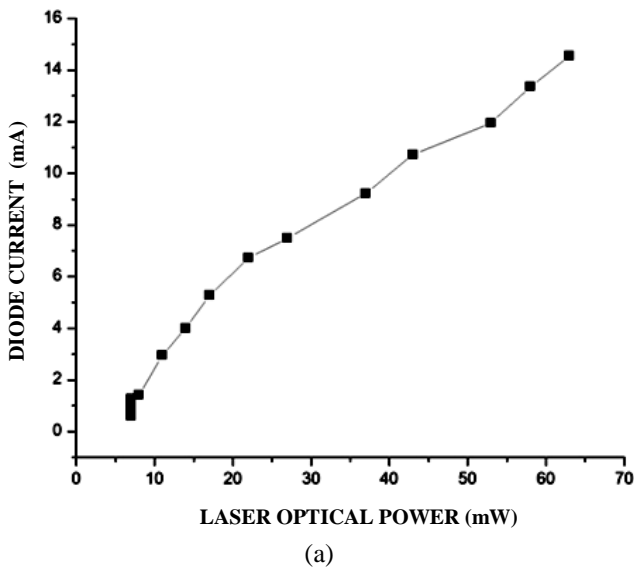


Fig.14. Experimental observation of (a) diode current with respect to laser optical power and (b) laser current vs. laser optical power

The Fig.14(b) shows the plot of laser current vs. laser optical power. It is seen from the characteristics the optical power rises from linearly after a certain value of the laser current, known as threshold current and, linearly changes with the diode current.

2.4 EXPERIMENT OF CHARACTERIZATION OF PHOTO DETECTOR

A photo detector is a device which converts optical power into electrical current. Usually it is a reverse biased p-n diode with an intrinsic region between the p- and n-region and hence the name PIN photodiode. An incident photon is absorbed by the semiconductor and results in the creation of electron hole pair in it. The generated electrons and holes are swept away from the junction region by the applied voltage resulting in a current in the external circuit. The amount of current depends on the light power incident on the photo detector. This is quantified by a quantity called responsivity R which is ratio of the current produced by the photo detector to the optical power incident on it. The responsivity is measured in units of amperes per watt (A/W). Thus if the responsivity of a photo detector is 0.4 A/W. When an optical power of 2mW incident on the photo detector would generate a current of 0.8mA. Photodiode can be operated either in photoconductive or in photovoltaic mode depending on whether they are externally biased (photoconductive). In the photovoltaic mode, (like in a solar cell) the voltage developed across the photodiode is a non linear function of the light intensity incident on it.

However when the photodiode is operated under reverse bias (photoconductive mode) the photocurrent generated is linearly dependent on the light intensity up to about six orders of magnitude of power variation. Since the junction capacitance decreases due to the reverse biasing, photodiode operated in the photoconductive mode is faster than the photovoltaic mode even though the former is noisier. Usually photodiodes in photoconductive mode are operated in conjunction with a transimpedance amplifier to convert the photocurrent developed

into a voltage that is easier to measure and for further amplification [3].

Bandwidth is another very important characteristic of a receiver. If modulated light wave is incident on a photo detector, then it should produce a similar modulated current output since the current generated by the photo detector depends on the corresponding incident light power. Now if the frequency of modulation of the input light wave is increased, it would be found that the depth of modulation in the output current reduces and for very high frequency of input light modulation, the current produced by the photo-detector remains almost constant. One of the primary reasons for the drop in the depth of modulation of the current output is the RC time constant of the photo detector circuit. The photo detector is characterized by a capacitance C and if the photo detector circuit has a resistance R then the photo detector circuit behaves like an RC circuit. It is well known that the speed of operation of an RC circuit is limited by the time constant RC . The corresponding BW is given by,

$$BW = \frac{0.7}{t_r} = \frac{1}{2\pi RC}$$

By measuring the rise time of the photo detector the quantity R can be estimated. Knowing the value of R , the corresponding capacitance of the photo detector can be found. On the load resistance R in the circuit. Although, large resistance will give a higher voltage at the output of the detector circuit, it would bring down the bandwidth of the detector and hence the high speed operation is not possible. Hence it can be understood that larger the bandwidth, the smaller will be the output and hence the signal to noise ratio (SNR). Table.2 and Table.3 shows the various observations under photoconductive mode and photovoltaic mode respectively.

Table.2. Observation under photoconductive mode

Resistance (k Ω)	Output voltage(V)	Rise time (μ s)	Bandwidth (MHz)	Observed capacitance (pF)
100	0.459	1.276	0.55	2.894
82	0.426	2.55	0.274	7.08
68	0.459	2.55	0.274	8.54
47	0.36	2.55	0.274	12.36
33	0.36	1.9138	0.36	13.39
22	0.39	1.9138	0.36	20.09
10	0.36	1.9138	0.36	44.21

Table.3. Observation under photovoltaic mode

Resistance (k Ω)	Output Voltage (V)	Rise time (μ s)	Bandwidth (MHz)	Observed capacitance (pF)
100	0.426	2.55	0.274	5.81
82	0.39	1.9138	0.36	5.39
68	0.39	3.1898	0.22	10.64
47	0.39	1.9138	0.36	9.4
33	0.39	2.55	0.274	17.6
22	0.39	1.9138	0.36	20.09
10	0.39	2.55	0.274	58.08

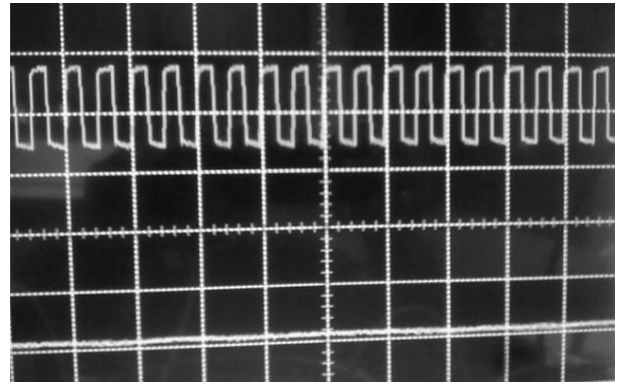


Fig.15. Output waveform of characteristics of photo-detector

The Fig.15 shows the output waveform of characteristics of photo-detector. Ideally the rise time of the photo detector is inversely proportional to and the output voltage is directly proportional to the resistance but according to our observations there are some variations as the data is experimental. The capacitance of the photodiode is calculated as per the formula in photovoltaic and photoconductive modes. This paper is very useful for beginners to study the different phenomena occurs in fiber communication links.

3. CONCLUSION

In this paper, we have provided the detailed description of attenuation and dispersion and its effect inside the optical fiber with some experimental result implemented on light runner. The paper describes the theoretical background of optical sources (LASER) and optical detector and its importance in modern technological scenario with some experimental result reflecting the characteristics of laser and optical detector.

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