Dispersion in Optical Fiber Communication

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Abstract: ***Optical fiber is one of the most important communication media in communication system. Due to its versatile nature and negligible transmission loss it is used in high speed data transmission. Dispersion in a single mode fiber is the bottleneck of long haul optical communication systems, which limits the bit rate and repeater-less distance. Chromatic dispersion (CD) of a single mode fiber (SMF) is an important aspect in a long-haul optical communication system. This paper provides a review of several published papers, white paper, and published articles in order to gain a complete picture about background of optical fiber. We discuss different types of fiber and its advantages. This paper also presents cause and effects of chromatic dispersion and describes different ways to measure it.***

Keywords: Optical Fiber, Dispersion, Chromatic Dispersion, Phase shift method, Pulse delay method.

1. Introduction

An optical fiber is a flexible filament of very clear glass capable of carrying information in the form of light. Optical fibers are hair-thin structures created by forming pre-forms, which are glass rods. The two main elements of an optical fiber are its core and cladding. The “core”, or the axial part of the optical fiber made of silica glass, is the light transmission area of the fiber. The “cladding” is the layer completely surrounding the core. The difference in refractive index between the core and cladding is less than 0.5 percent. Optical fiber played a very important role due to its wide properties like high bandwidth, long distance transmission, and high level of security.

Dispersion is the main performance limiting factor in optical fiber communication. Dispersion greatly hampers the performance of optical fiber communication. When a pulse travels through an optical fiber due to dispersion it becomes broadened. The dispersion is proportional to the length of the fiber. Dispersion is a consequence of the physical properties of the transmission medium. Single-mode fibers, used in high-speed optical networks, are subject to Chromatic Dispersion (CD) that causes pulse broadening depending on wavelength, and to Polarization Mode Dispersion (PMD) that causes pulse broadening depending on polarization. Excessive spreading will cause bits to “overflow” their intended time slots and overlap adjacent bits. The receiver may then have difficulty discerning and properly interpreting adjacent bits, increasing the Bit Error Rate. To preserve the transmission quality, the maximum amount of time dispersion must be limited to a small proportion of the signal bit rate, typically 10% of the bit time.

2. Literature Review

Hwang and Choi has proposed a complex network, where WLANs are linked into a fibre optic network to expand DAS in distribution lines in cost effective manner. They have designed a DAS wireless bridge for proposed communication network using IEEE 802.11 a WLAN technology and feasibility checked experimentally in terms of effective transmission speed and sensitivity of signal received. **Malekiah et al.** have analysed optical back propagation (OBP) technique that utilised two highly non linear fibres to compensate for transmission fibre non-linear effects. Sheng Li has reviewed the emerging technologies for advancing the fibre optic data communication bandwidth for the next generation broadband networks. **Alnajjar et al**. have proposed a smart communication platform system (SCPS) based station to verify the aptitude of system performance used to handle and support the communication network in disaster areas. **Li et al**., experimentally demonstrated for the first time, millimeter -wave(mm-wave) generation in the E-band (71–76 GHz and 81–86 GHz) based on photonics generation technique.

Narimanov et al. have developed a method to calculate the information capacity of a nonlinear channel and computed the decrease in channel capacity for fibre optic communication systems. A new methodology to design long-haul fibre optic communication systems has been designed by Peddanarappagari and Brandt Pearce. **Taylor and Thacker et al**. reviewed the application of fibre optic communication for satellite communications due to its low weight, large bandwidth capacity and simple architecture for data bussing, electromagnetic interference (EMI), invulnerability and cost-effectiveness. **M.I. Hayee and A. E. Willner analyzed** 10 Gb/s non dispersion managed and dispersion managed wavelength division multiplexed system that use pre compensation, post compensation or dual compensation of each channel to minimize dispersion and nonlinear effects. They find that dual compensation gives the minimal penalty for each dispersion managed WDM systems. **T.N. Nielsen et al.** proposed a compact tunable fiber Bragg grating (FBG) that uses distributed thin film heaters on the surface of the fiber to dynamically optimize the post dispersion compensation at 40 Gb/s non return to zero transmission system. They have demonstrated first dispersion compensating FBG at long pseudorandom bit sequence pattern lengths. They find that a device itself requires only a Bragg grating and a tapered thin metal film coating to shift and chirp the FBG wavelength by changing the applied current through the film which optimize time varying dispersion maps and can reduce power penalty associated with nonlinear transmission impairments and other variations.

3. Classification of Fiber

We categorize the fiber optic communication in two categories:

1. Step Index
    - Single Mode
    - Multimode

2. Graded Index

1. Step Index

The step Index types of fibers have sharp boundaries between the core and cladding, with clearly defined indices of refraction. The entire core uses single index of refraction.

It has a higher capacity to transmit information as it can retain the fidelity of each light pulse over longer distances and exhibits no dispersion caused by the multiple modes. It has also lower fibre attenuation than multimode fibre.

- **Single Mode Step Index**
  Single mode fiber has small central core diameter of 8 to 9 microns, which only allows one light path or mode. Light rays, that enter the fibre, either propagate down the core or are reflected only few times. All rays approximately follow the same time to travel the length of the fibre.
- **Multimode Step-Index Fiber**
  Multimode fiber has a core diameter of 50 or 62.5 microns (sometimes even larger). It allows several light paths or modes. This causes modal dispersion – some modes take longer to pass through the fiber than others because they travel a longer distance.

2. Multimode Graded-Index Fiber

Graded-index refers to the fact that the refractive index of the core gradually decreases farther from the centre of the core. The increased refraction in the centre of the core slows the speed of some light rays, allowing all the light rays to reach the receiving end at approximately the same time, reducing dispersion.

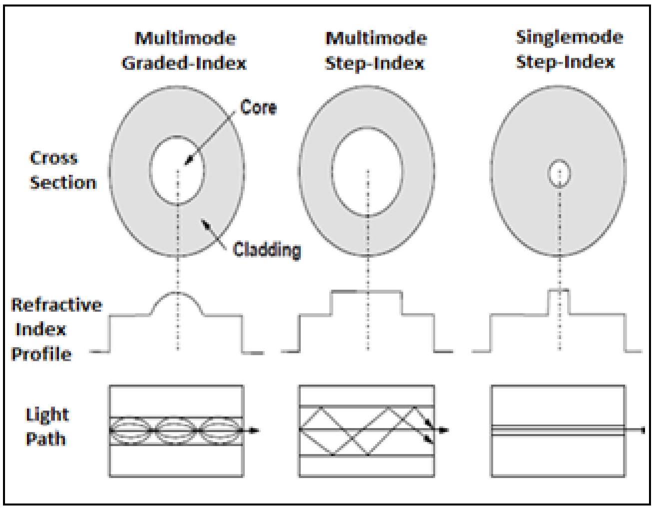

Figure 1: Fiber Optics Modes

Advantage of Optical Fiber Communication:

I. Enormous potential bandwidth
II. Small size and weight
III. Signal security:
IV. Low transmission loss
V. Potential low cost

Disadvantage of Optical Fiber Communication

I. It requires a higher initial cost in installation
II. Although the fiber cost is low, the connector and interfacing between the fiber optic costs a lot.
III. Fiber optic requires specialized and sophisticated tools for maintenance and repairing.

4. Dispersion

Dispersion is defined as pulse spreading in an optical fiber. As a pulse of light propagates through a fiber, elements such as numerical aperture, core diameter, refractive index profile, wavelength, and laser line width cause the pulse to broaden. Dispersion increases along the fiber length. The overall effect of dispersion on the performance of a fiber optic system is known as Intersymbol Interference (ISI). Intersymbol interference occurs when the pulse spreading caused by dispersion causes the output pulses of a system to overlap, rendering them undetectable. Dispersion is generally divided into three categories: modal dispersion, chromatic dispersion and polarization mode dispersion.

I. **Modal dispersion** is defined as pulse spreading caused by the time delay between lower-order modes and higher-order modes. Modal dispersion is problematic in multimode fiber, causing bandwidth limitation.
II. **Chromatic Dispersion (CD**) is pulse spreading due to the fact that different wavelengths of light propagate at slightly different velocities through the fiber because the index of refraction of glass fiber is a wavelength-dependent quantity; different wavelengths propagate at different velocities**.**
III. **Polarization Mode** Dispersion (PMD) occurs due to birefringence along the length of the fiber that causes different polarization modes to travel at different speeds which will lead to rotation of polarization orientation along the fiber.

4.1 CD of Current Network Spans

The Chromatic Dispersion of a fiber is expressed in ps/(nm*km), representing the differential delay, or time spreading (in ps), for a source with a spectral width of 1 nm traveling on 1 km of the fiber. It depends on the fiber type, and it limits the bit rate or the transmission distance for a good quality of service.

As a consequence of its optical characteristics, the Chromatic Dispersion of a fiber can be changed by acting on the physical properties of the material. To reduce fiber dispersion, new types of fiber were invented, including dispersion-shifted fibers (ITU G.653) and non-zero dispersion-shifted fiber (ITU G.655). The most commonly deployed fiber in networks (ITU G.652), called "dispersion-unshifted" single mode fiber, has a small chromatic dispersion in the optical window around 1310 nm, but exhibits a higher CD in the 1550 nm region. This dispersion limits the possible transmission length without compensation on OC- 768/STM-256 DWDM networks.

ITU G.653 is a dispersion-shifted fiber (DSF), designed to minimize chromatic dispersion in the 1550 nm window with zero dispersion between 1525 nm and 1575 nm. But this type of fiber has several drawbacks, such as higher polarization mode dispersion than ITU G.652, and a high Four Wave Mixing risk, rendering DWDM practically impossible. For these reasons, another single mode fiber was developed: the Non-Zero Dispersion-Shifted Fiber (NZDSF). NZDSF fibers have now replaced DSF fibers, which are not used anymore.

The ITU G.655 Non-Zero Dispersion-Shifted Fibers were developed to eliminate non-linear effects experienced on DSF fibers. They were developed especially for DWDM applications in the 1550 nm window. They have a cut-off wavelength around 1310 nm, limiting their operation around this wavelength.

4.2 CD Limit and Compensation

The chromatic dispersion in fiber causes a pulse broadening and degrades the transmission quality, limiting the distance a digital signal can travel before needing regeneration or compensation. For DWDM systems using DFB lasers, the maximum length of a link before being affected by chromatic dispersion is commonly calculated with the following equation:

$$L= 104{,}00/CD * B^2$$

L is the link distance in km, CD is the chromatic dispersion in ps/(nm * km), and B is the bit rate in Gbps.

Fortunately, CD is quite stable, predictable, and controllable. Dispersion Compensation Fiber (DCF), with its large negative CD coefficient, can be inserted into the link at regular intervals to minimize its global chromatic dispersion. While each spool of DCF adequately solves chromatic dispersion for one channel, this is not usually the case for all channels on a DWDM link. At the extreme wavelengths of a band, dispersion still accumulates and can be a significant problem. In this case, a tunable compensation module may be necessary at the receiver. Therefore, chromatic dispersion measurement is essential in the field to verify the types of installed fibers. Such measurements assess if and how the fibers can be upgraded to transmit higher bit rates, verify fiber zero point and slope for new installations, and carefully evaluate compensation plans.

4.3 CD Measurement Methods

In the field, there are three main methods for determining the chromatic dispersion of an optical fiber. These are described by three TIA/EIA industry standards: the pulse-delay method (FOTP-168 standard), the modulated phase-shift method (FOTP-169 standard), and the differential phase shift method (FOTP-175 standard). These methods all measure first the time delay, in ps, as a function of the wavelength. They then deduce the chromatic dispersion coefficient, in ps/(nm*km), from the slope of this delay curve and from the length of the link.

Phase-shift and differential phase-shift methods are quite similar. In both methods, a modulated source is injected at the input of the fiber under test. The phase of the sinusoidal modulating signal is analyzed at the output of the fiber and compared to the phase of a reference signal, modulated with the same frequency. In the phase-shift method, the reference signal has a fixed wavelength, while the other modulated signal is tuned in wavelengths. In the differential phase-shift method, both signals are tuned in wavelengths, with a fixed wavelength interval. The analyzed modulated signal, tuned in wavelengths, is compared to a close reference signal, also tuned in wavelength, but the wavelength gap is constant. The time delay of the link is deduced from the phase-shift measurement, using the relationship between the delay (t), the phase (φ), and the modulation frequency (f):

$$\Delta t = \Delta\varphi / 2\pi f$$

The phase-shift methods assume there is access to both ends of the fiber under test, with a transmitter unit connected at the input, and a receiver unit at the output of the fiber. The wavelength selection can be achieved either at the transmitter unit level, using a tunable laser, or at the receiver unit level, with a broadband source at the input and a wavelength tunable filter in the receiver unit. This filter must be spectrally thin (FWHM < 1 nm) to ensure low impact on the measurement accuracy. This second alternative is commonly used in the differential phase-shift method. One disadvantage of this method is that the phase shift is evaluated comparing two signals with close wavelengths. Increasing the wavelength interval between the two modulated signals will increase the accuracy of the delay at one individual wavelength point, but will decrease the number data points that can be acquired to trace the delay curve, leading to a lower accuracy in the CD coefficient computation. A compromise has to be found between the wavelength interval for the differential phase-shift calculation and the number of acquired points to fit the delay curve, but achieving this is not straightforward.

The phase-shift methods are two-ended solutions, allowing measurement through amplifiers on long-haul links. They measure the CD with high accuracy, since the wavelengths of modulated signals are known accurately, and many points of measurements can be acquired, leading to a better fit of the delay curve. However, these solutions are expensive and thus may not be appropriate for metropolitan applications. They require operators at both ends of the link, often with bulky instruments.

The pulse-delay methods measure the time that different wavelength carriers travel through the fiber under test, either by photon counting (a direct but very complex method), or by measuring the link length with a multi-wavelength OTDR. The CD-OTDR launches multiple laser pulses into one end of the fiber under test, ideally using more than four different wavelengths for better accuracy. It then analyzes the time to return after a back-reflection from the connector at the other end. The time delay as a function of the wavelength is deduced by comparing the times of flight of the laser pulses.

The CD-OTDR solution is highly cost-effective, primarily because the initial cost of the instrument is far lower than that of a phase-shift setup. Furthermore, the CD-OTDR is also a complete 3-wavelength OTDR module, which is at the heart of any fiber characterization effort. The CD-OTDR combines two test setups in a single, small instrument. It is a one-ended test solution, resulting in less manpower to carry out the test, less training cost, and lower transportation costs. It can be less accurate than a phase-shift tester, but accuracy better than 5% can be achieved with a 6 wavelength CD-OTDR. This is sufficient to assess a link's chromatic dispersion, which is a stable and predictable parameter. The CD-OTDR is therefore a good alternative to phase-shift testing in metro rings and regional networks.

Table1: Comparison table of CD measurement methods

Phase-shift method	*CD-OTDR method*
long-haul link	metro & access link
two-ended measurement	one-ended measurement
good accuracy (depending on number of acquired points	<5% with 6-wavelength CD-OTDR
high	low

5. Conclusion

The growth of the fiber optics industry over the past few years has been explosive. Analysts expect that this industry will continue to grow at a tremendous rate well into the next decade. Dispersion in optical fibers limits the quality of signal transmission. Chromatic dispersion must be measured to assess the potential of upgrading networks to higher transmission speeds, or to evaluate the need for compensations. In this paper, various types of optical fiber have been discussed. The paper also described the cause and effects of chromatic dispersion in optical fiber and details of CD measurement methods. Our future work will be to find out different methods to reduce dispersion in optical fiber.

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