AN EFFECTIVE ANALYSIS AND MEASUREMENTS OF DISPERSIONS IN OPTICAL COMMUNICATION

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***Abstract* -** Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information. Fiber is preferred over electrical cabling when high bandwidth, long distance, or immunity to electromagnetic interference is required. 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. The bitrates must be low enough to ensure that pulses are farther apart and therefore the greater dispersion can be tolerated. Dispersion can be caused by Modal dispersion, Material dispersion, Waveguide dispersion. Chromatic dispersion in a single mode fibre is an important aspect in long haul optical communication system. In this paper we are going to present the effects of dispersions and describe different ways to measure it.

***Index terms* -** Optical fibre, Dispersions; Modal dispersion; Chromatic dispersion; Material dispersion; Waveguide dispersion; Phase shift method; Pulse delay method.

I. INTRODUCTION

Optical communication is communication at a distance using light to carry information. An optical communication system uses a transmitter, which encodes a message into an optical signal, a channel, which carries the signal to its destination, and a receiver, which reproduces the message from the received optical signal. When electronic equipment is not employed the 'receiver' is a person visually observing and interpreting a signal, which may be either simple or complex. Free-space optical communication has been deployed in space, while terrestrial forms are naturally limited by geography, weather and the availability of light. Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information. Fiber is preferred over electrical cabling when high bandwidth, long distance, or immunity to electromagnetic interference is required. Optical fiber is used by many telecommunications companies to transmit telephone signals, Internet communication, and cable television signals. Researchers at Bell Labs have reached internet speeds of over 100 petabit×kilometer per second using fiber-optic communication. Copper wires are used in data transmission since the invention of telephone. Optical Fiber is new medium, in which information (voice, Data or Video) is transmitted through a glass or plastic fiber, in the form of light. The field of applied science and engineering concerned with the design and application of optical fibers is known as fiber optics. Optical fibers are widely used in fiber optics, which permits transmission over longer distances and at higher bandwidth (data rates) than other forms of communication. Optical fibers may be connected to each other or can be terminated at the end by means of connectors.

II. DISPERSION

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. The bitrates must be low enough to ensure that pulses are farther apart and therefore the greater dispersion can be tolerated. Dispersions in optical fibre communications can be occurred in following ways:

A. *Modal Dispersion*
B. *Material Dispersion*
C. *Waveguide dispersion*
D. *Chromatic dispersion*

1) *Modal dispersion*

Modal dispersion is the phenomenon that the group velocity of light propagating in a multimode fiber depends not only on the optical frequency but also on the propagation mode involved.

The strength of intermodal dispersion can be quantified as the differential mode delay (DMD). It depends strongly on the refractive index profile of the fiber in and around the fiber core. For example, for a step-index profile the higher-order modes have lower group velocities, and this can lead to differential group delays of the order of 10 ps/m = 10 ns/km. It is then hardly possible to realize data rates of multiple Gbit/s in an fiber-optic link with a kilometer length. In systems for optical fiber communications based on multimode fibers, intermodal dispersion can severely limit the achievable data transmission rate (bit rate). In order to avoid strong signal distortion, it is usually necessary to keep the pulses long enough to maintain a reasonable temporal overlap of components from different modes, and this unavoidably sets a limit on the data rate.

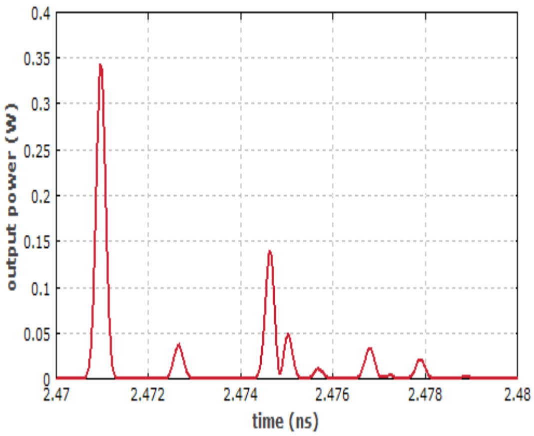

Fig.1:Output power versus time for a 200-fs input pulse injected into a 50 cm long multimode fiber. The numerical simulation has been done with the RP Fiber Power software

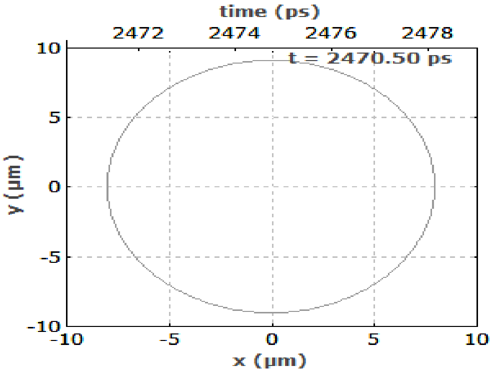

Fig.2:Time-dependent output beam profile for the same situation as in Figure 1.

2) *Material and Waveguide Dispersion*

Material refractive index varies with wavelength and therefore causes the group velocity to vary; it is classified as material dispersion. The wavelength dependence of refractive index can be expressed by Sellmeier's equation. Waveguide dispersion is the result of wavelength-dependence of the propagation constant of the optical waveguide. It is important in single-mode waveguides. The larger the wavelength, the more the fundamental mode will spread from the core into the cladding. This causes the fundamental mode to propagate faster. The material and waveguide dispersion effect is important when the grating filter has a broadband response, such as a codirectional waveguide coupler and a long period fiber grating. In these cases, the waveguide mode constants are re-calculated for different wavelength by considering material dispersion. Optical telecommunication fibers are usually made from silica glasses. The high purity glass is called the host material or substrate. Its bulk refractive index is usually the fiber cladding refractive index. The fiber core is formed by adding dopant materials to the host material. To change the refractive index of optical fiber, pure silica is often doped with dopants. For example, adding germanium can result in an increase in the refractive index, while adding fluorine reduces it. The refractive index of doped material can be determined by the linear relationship between the doped material's mole percentage and permittivity.Assume that n0 is the refractive index of the host material and n1 is the refractive index of m1 mole-percentage doped material. Then, the refractive index n of m molepercentage doped material can be interpolated as:

$$n^2 = n_0^2 + \frac{m}{m_1}(n_1^2 + n_0^2)$$

when the refractive index at a central wavelength λ 0, n(λ0) and the host and dopant material dispersion curves, nhost(λ) and ndopant(λ) are defined, the dependence of the refractive index with wavelength, n(λ), is calculated based on the following equation:

$$n^2(\lambda) = n_{host}^2(\lambda) + \frac{n^2(\lambda_0) - n_{host}^2(\lambda_0)}{n_{dopant}^2(\lambda_0) - n_{host}^2(\lambda_0)} \cdot [n_{dopant}^2(\lambda) - n_{host}^2(\lambda)]$$

This equation is the same as (11), with the fraction m/m_1 estimated by comparing, at the centre wavelength λ_0, the refractive index of the given material with the index of a doped material with known Sellmeier coefficients ndopant. OptiGrating uses Equation 12 to handle the case where the Sellmeier coefficients are known for material of just one doping concentration. If the material in question has the same dopant, but with an unknown concentration, the fraction in Equation 12 will estimate the concentration by comparing the given index n(λ0) with the reference index ndopant(λ0). With the doping concentration estimated this way, the refractive index at other wavelengths is accurately estimated by Equation 12. On the other hand, in the case where the Sellmeier coefficients are exacly known for the given material, the user can enterthem himself in OptiGrating's Sellmeier Coefficient Library. OptiGrating still uses Equation 12, since in this case the fraction is calculated as unity, and the left hand side is assigned to ndopant(λ0) for all wavelengths directly.

3) Chromatic dispersion

Chromatic dispersion is a phenomenon that is an important factor in fiber optic communications. It is the result of the different colors, or wavelengths, in a light beam arriving at their destination at slightly different times. The result is a spreading, or dispersion, of the on-off light pulses that convey digital information. Special care must be taken to compensate for this dispersion so that the optical fiber delivers its maximum capacity. Chromatic dispersion is commonplace, as it is actually what causes rainbows - sunlight is dispersed by droplets of water in the air. Sir Isaac Newton observed this phenomenon when he passed sunlight through a prism and saw it diverge into a spectrum of different colors. This dispersion occurs because different colors, or light frequencies, act slightly differently as they pass through a medium such as glass. In fiber-based systems, an optical fiber, comprised of a core and cladding with differing refractive index materials, inevitably causes some wavelengths of light to travel slower or faster than others. Chromatic dispersion is a serious consideration in long-haul optical fibers. Its effect is essentially to stretch or flatten the initially sharply-defined binary pulses of information. This degradation makes the signals (1s and 0s) more difficult to distinguish from each other at the far end of the fiber. The result is that at any given length, the effective information capacity, or bandwidth, of the fiber optic cable can be significantly reduced. Dispersion is added as the modulated beam of light, consisting of a number of closely spaced wavelengths, travels down this nearly transparent waveguide. The bottom line is that chromatic dispersion becomes a major consideration and must be accounted for when developing or deploying fiber optic equipment for use in telecommunications, cable TV, or other high-speed optical networks. Fortunately, techniques have been developed that help compensate for the negative effects of chromatic dispersion. One method involves pre-compensating the signal for the anticipated dispersion before it's sent down the optical fiber. Another method calls for using dispersion compensating fiber at the end of a length to correct or reverse the dispersion that was realized as the signal traversed the optical fiber. As a result, these techniques are widely used to help solve the problem of chromatic dispersion.

4) Measurement methods

Methods to measure chromatic dispersion: the modulation phase-shift method (MPS) and the differential phase-shift method (DPS). (Other methods, such as swept-laser interferometry, exist, but they're not as common.) Both methods let you calculate chromatic dispersion in lengths of optical fibers from less than 0.2 m to thousands of kilometers, and you can use these methods to analyze the chromatic dispersion in components such as interleavers, filters, and fiber Bragg gratings.These two methods measure the phase shift of a modulated optical signal as it passes through a device under test (DUT). The resulting test data relates the measured phase change to specific wavelengths.The majority of test systems used to measure chromatic dispersion in installed fiber employ the DPS method, which provides faster measurements than the MPS method. In most cases, though, the MPS method provides superior accuracy. If you need to measure the characteristics of installed fiber, use the DPS method. When you must make high-accuracy measurements on narrowband components, use the MPS method.

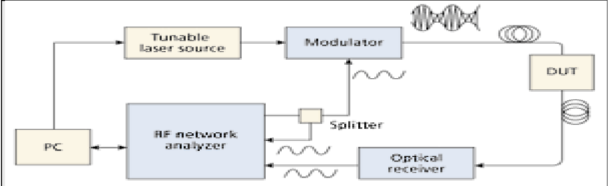

Fig.3:The MPS method measures the phase difference between a transmitted and received signal. The RF network analyzer modulates the amplitude of the laser's signal.

Test systems that use the MPS method directly measure changes in the phase of a modulated pulse and compute group-delay values. The MPS method uses a high-frequency sine wave, typically between 10 MHz and a few GHz, from an RF network analyzer to modulate the intensity of light produced by a tunable laser source (TLS) (Figure 3). Chromatic-dispersion test systems based on the MPS method can resolve a delay as short as 0.001 ps, or 1 fs.

The modulated signal passes through a DUT—assume it's a length of optical fiber—and reaches an optical receiver that demodulates it. The RF network analyzer measures the phase difference between the modulated signal that passes through the fiber and the original modulation signal. While the PC changes the wavelength of the TLS in small steps, a fiber with chromatic-dispersion characteristics causes a slight change in modulation phase. You can calculate the relative group delay , dt : $dt = (Df/360) \times (1/f_m)$

where: Df = the phase change in degrees induced by the wavelength shift f_m= the modulation frequency in Hz Then, you can calculate the dispersion,

D: $D = (dt/dl) \times (1/L)$

where: dl=the wavelength change in meters
L = the length of the optical fiber in meters

Once you set up an MPS test system, it requires no manual adjustments. The laser source determines the wavelength accuracy, and the crystal time base in the network analyzer determines the timing accuracy. Temperature changes can cause instruments to drift, though, so you should make chromatic-dispersion measurements quickly. A typical MPS measurement can take from a few seconds to a few minutes. A test system can perform MPS measurements by using a TLS in either stepped mode or swept mode. In the stepped mode, after the TLS "steps" to a new wavelength, the instrument acquires the phase data. Optical-fiber measurements require steps of 0.5–1 nm, and narrowband components require steps of 1–100 pm.

DPS dithers wavelengths

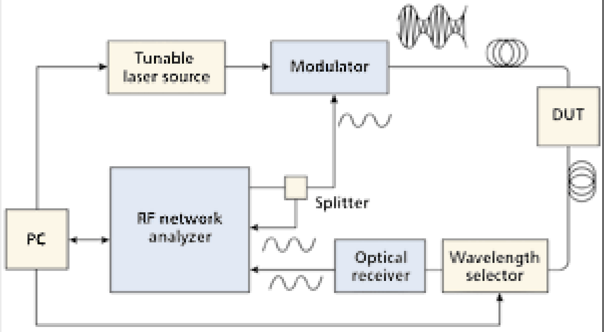

Fig.4: Like the MPS method, the DPS method also modulates the amplitude of the laser's signal. But the DPS method also slightly varies, or dithers, the laser's wavelength.

Unlike the MPS method that measures group delay, the DPS method directly measures chromatic dispersion. Both methods modulate the amplitude of a laser signal. But test systems based on the DPS method (Figure 4) also "dither" the laser's wavelength around the central wavelength. Dithering modulates the wavelength within a frequency range of about 100 MHz to 3 GHz. Thus, the signal from the DUT exhibits both phase and wavelength changes.

A DPS test system directly determines the value of chromatic dispersion at a selected wavelength by measuring the change in group delay across a small (dithered) wavelength interval. The resulting chromatic dispersion represents the average dispersion over the wavelength interval. The DPS method can provide rapid measurements, but because the dithering produces an average value, that value may differ slightly from the actual dispersion. In most cases, that's an acceptable tradeoff for the measurement speed gained.

The group delay in narrowband components may vary rapidly across the component's bandwidth. Thus, resolving the group delay variation exhibited by such components requires lower modulation frequencies and small wavelength steps.

A DPS test system made up of the blocks shown in Figure 4 will calculate the dispersion, D, in units of ps/nm-km using the following equation:

$D = df / 360 \times (dl) \times L \times f_m$ where: df = the phase change in degrees induced by the wavelength shift fm = the RF modulation frequency in Hz L = the length of the optical fiber in meters

Optimize measurement accuracy.Until recently, chromatic-dispersion testing focused solely on optical fiber. The optical characteristics of fiber change smoothly with respect to wavelength, and the fiber covers a relatively wide bandwidth. Thus, tests could use relatively large wavelength steps, usually 0.5–1 nm.

But newer dense wavelength-division multiplex (DWDM) systems include narrowband devices such as filters and multiplexes that operate over a narrow band of wavelengths. These devices require testing over small wavelength intervals of 1–100 pm.

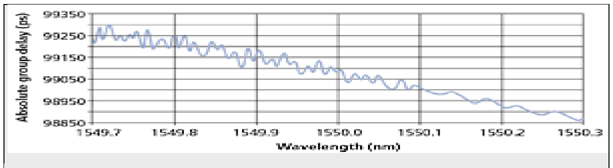

Fig.5:Only scanning wavelengths in small steps reveals the ripple in the group delay from an optical component. The ripples can cause problems in DWDM systems that rely on closely spaced wavelengths.

Some of these narrowband devices produce a high-frequency ripple in the group delay. This characteristic can cause problems for system designers, because even a small change in wavelength may cause a large change in the magnitude and sign of the chromatic dispersion. Figure 5 shows the ripple in the group delay for an optical component measured with an MPS test system using 0.1-pm wavelength steps and a 100-MHz modulation frequency.

Reducing the modulation frequency and wavelength step provides better measurement resolution for narrowband components. But these smaller and smaller steps eventually run into a noise limit. To reduce noise, an instrument can take more samples and average them, but the additional measurements increase the overall test time. Lowering the modulation frequency and using smaller wavelength steps can produce a phase change that exceeds the range of the phase detector, thus producing an aliasing error. (Some commercial test systems automatically avoid such conditions for fiber test.)

Typically, for optical-fiber measurements, you can choose a high-modulation frequency (2 GHz) and a large wavelength step (1 nm). For narrowband measurements, though, you should choose a modulation frequency below 500 MHz and a wavelength step of less than 100 pm.

The inherent wavelength accuracy (0.1 nm) of a tunable laser may suffice for testing narrowband components. But if you need higher wavelength accuracy, such as when you're testing a high-speed, long-haul fiber link, you'll need to substitute a tunable external-cavity laser for the TLS and add a wavelength meter to your test system. A cavity laser provides finer wavelength control, and a wavelength meter provides a precise wavelength reference. Routing some of the laser's output to the wavelength meter and monitoring the wavelength meter with the test system's PC provides a control loop that keeps the tunable laser on a set wavelength.

5) Control dispersion

Control of chromatic dispersion in optical transmission systems proves critical to the design and construction of long-haul, high-speed telecommunication systems. Designers must reduce the dispersion so error rates in such systems reach an acceptable level. A range of components such as dispersion-compensating fiber and fiber Bragg gratings and techniques such as using the soliton-like behavior of optical pulses now mitigate the effects of dispersion. Many of these techniques were used first in submarine cable systems, in which multiplexed-wavelength signals at high bit rates travel over long distances.

Table 1. The relation between dispersion, bit rates, and link length.

Note: Data assume 1 dB dispersion penalty; standard single-mode fiber with dispersion = 17 ps/nm-km, and external modulation.

Bit rate (Gbps)	2.5	10	40
Maximum dispersion (ps/nm)	16,000	1000	63
Maximum link length (km)	941	59	4

III. CONCLUSION

Fiber optic technology is the new trend in communications industry and is steadily and effectively replacing the copper wire system for transmission of signals. Dispersion can be avoided by using smaller core diameters which allows fewer modes. And also usage of single mode fiber permits no modal dispersion. By using a graded index fiber so that light rays that allow longer paths to travel at a faster velocity and there by arrive at the other end of the fiber nearly at the same time. 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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