Chromatic dispersion:

why it is a critical parameter to measure during fiber characterization

white paper

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What is chromatic dispersion?

Let's start with some definitions first.

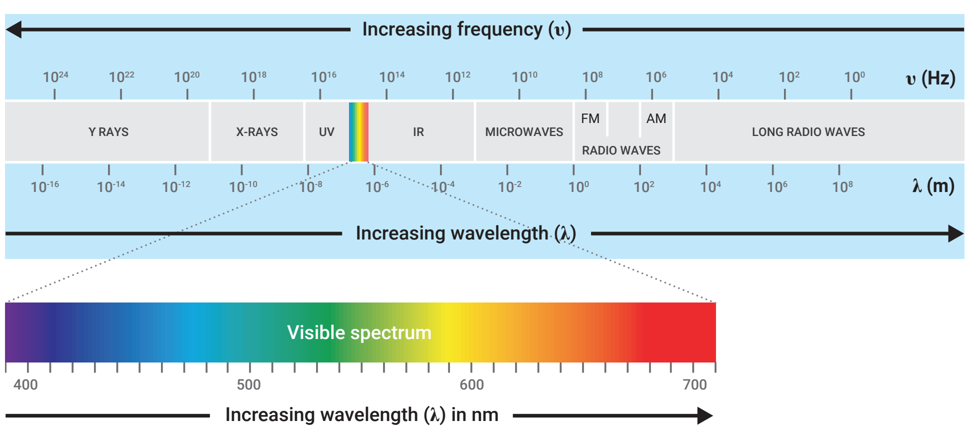
- **Chromatic** refers to color or color phenomena[1]
- **Dispersion** refers to the separation of light into colors by refraction or diffraction[2]

We see the effects of chromatic dispersion in our daily lives by looking no further than natural sunlight refracting through a prism of glass and separating the sun's white light into a rainbow of colors. But why does this happen?

Dispersion occurs because the index of refraction for a material like glass or water varies with the wavelength of light. Every color of light we see has a different wavelength and each color or wavelength travels at a different speed; shorter wavelengths (i.e., violet and blue) travel faster than longer wavelengths (i.e., orange and red). In addition, the index of refraction is wavelength-dependent, shorter wavelengths (like the visible violet and blue light) bend more than longer wavelengths (visible orange and red light) when transitioning from air to the denser prism material. This separation of colors is what creates the rainbow effect we see. Moreover, we can visualize the broadening or spreading of the color spectrum as the polychromatic light makes its way through the prism and out the other side to illuminate our walls or floors.

Index of refraction is the ratio between the speed of the light in a vacuum and speed of light in a fiber ($n = \frac{c}{v}$)

Visible light belongs to the electromagnetic radiation spectrum, which is used to classify different wavelengths from radio waves (long wavelengths) to gamma waves (extremely short wavelengths). In fiber optics, the electromagnetic spectrum used falls into the infrared, non-visible, spectrum. A common wavelength in fiber optic communication is 1550 nm or 193.48 THz. The same chromatic dispersion we see in the visible spectrum happens in the infrared spectrum too. This is why we need to understand the impact of chromatic dispersion in fiber optic communications.

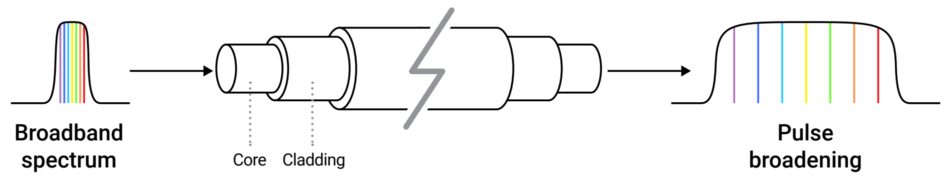


1. www.merriam-webster.com/dictionary/chromatic
2. www.merriam-webster.com/dictionary/dispersion

> Chromatic dispersion is effectively the spreading of a broadband spectrum pulse over long distances.

Chromatic dispersion in fiber optic communications

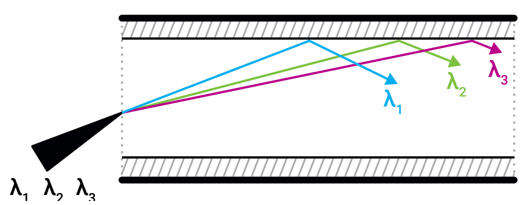
Chromatic dispersion is a natural characteristic of optical fibers however, every fiber type will be different so measuring chromatic dispersion is required in order to properly control and manage this characteristic. The unit of measurement for chromatic dispersion is **picoseconds per nanometer kilometer** (ps/[nm·km]). This means that for every kilometer of fiber, a pulse with a spectral width of one nanometer will spread out by one picosecond.



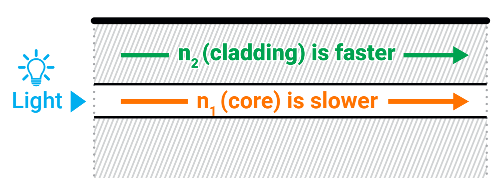
Chromatic dispersion can be broken down into two different categories: material dispersion and waveguide dispersion.

- **Material dispersion** is where different wavelengths of the infrared portion of the electromagnetic spectrum travel at different speeds through the fiber (reminder, shorter wavelengths travel faster than longer wavelengths). The result is that each wavelength will arrive at the far end transceiver at a different time.
- **Waveguide dispersion** is caused by the different refractive indexes of the core and cladding of a fiber because light will travel in both the core as well as the cladding. Waveguide dispersion can cause wavelengths to have a different polarity than wavelengths in material dispersion, which can result in the canceling out of the wavelength (chromatic dispersion becomes zero). This is called the *zero-dispersion wavelength* or *lambda-0* (λ_0).

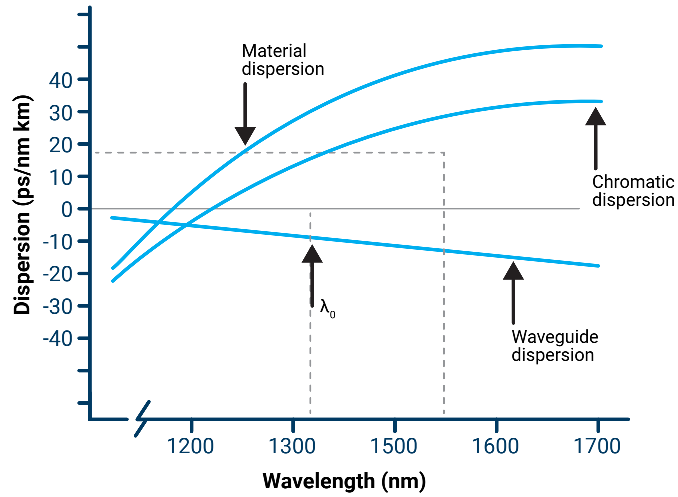
Chromatic dispersion is divided into two sub-categories



Material dispersion
Material dispersion arises due to the inherent properties of the fiber core material, where different wavelengths of light experience different velocities as they travel through the core. This type of dispersion can cause group delay distortion, thus impacting the transmitted data.

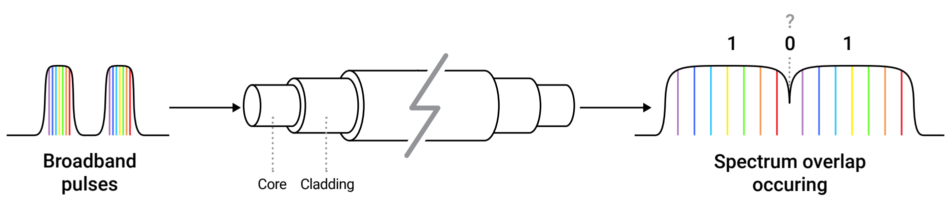


Waveguide dispersion
Waveguide dispersion in optical fibers occurs because the signal travels in both the core and cladding, causing the mode field diameter to impact the average dispersion index, leading to variations in signal velocity with wavelengh.



> In fiber optic testing, chromatic dispersion is a critical parameter to measure and manage, as it can impact the overall performance of the fiber optic communication system.

What's more, a sequence of light pulses, data represented by a series of 1's and 0's, will spread in time due to chromatic dispersion and potentially overlap, causing bit errors (i.e., symbol interference) to occur. This means the receiver at the end will not be able to detect if the signal is a zero or another one in between the two bits that were sent. And these type of receiving errors increase with distance. An eye diagram is one of the best ways to characterize the quality of a link, or the clarity of a transmission. It includes the rising edge, falling edge, the ones and zeros. The longer the distance, the noisier it gets due to chromatic dispersion caused by the refractive index of the glass. The natural chromatic dispersion of a fiber will be higher if transmission is not set according to waveguide dispersion.



In fiber optic testing, chromatic dispersion is a critical parameter to measure and manage, as it can impact the overall performance of the fiber optic communication system. In ITU-T G.650.3, chromatic dispersion is documented as a test requirement, along with OTDR and OLTS testing. Testing for chromatic dispersion involves analyzing the delay in the arrival of different wavelengths and assessing their impact on signal quality. This is essential for ensuring the proper functioning of the fiber optic network and optimizing its performance. Other industry recommendations for chromatic dispersion testing include TIA-455-175 and IEC 60793-1-42.

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Chromatic dispersion and fiber types

Many fiber types are available on the market and those available for fiber optic communication are defined by the ITU.

The most popular single mode fiber type by far (i.e., 90%) is defined in **ITU-T recommendation G.652**. This is considered a non-dispersion shifted fiber (NDSF) type, also known as a "natural dispersion" fiber. The zero-dispersion wavelength of **G.652** fiber is around 1310 nm. The dispersion is low to none at 1310 nm and high at 1550 nm; the flip side is that the attenuation is quite high at 1310 nm yet low at 1550 nm. If a deployment is for a long-haul fiber deployment, then a low attenuation factor is more important than a high dispersion factor. The chromatic dispersion coefficient of G.652 fiber is 17 picosecond per nanometer kilometers at 1550 nm.

In the 1990's, in an effort to have a fiber with low attenuation at 1550 nm and low dispersion at 1550 nm, the **ITU-T G.653** dispersion shifted fiber (DSF) was created. The downside is that this fiber suffered from high non-linear effects (NLE), resulting in a negative impact to signal quality and performance. NLE could be due to impact from phase-modulation and four wave mixing. This fiber type was not practical for wavelength division multiplexing (WDM) deployments.

ITU-T G.654, also known as cut-off shifted fiber or ultra-low loss fiber, is typically used in subsea/submarine cable deployments and long-haul terrestrial applications. There are a number of variations of G.654 fibers with slightly different chromatic dispersion coefficients. For example, the chromatic dispersion coefficient of G.654.A fiber is 20 picosecond per nanometer kilometers at 1550 nm while the chromatic dispersion coefficient of G.654.D fiber is 23 picosecond per nanometer kilometers at 1550 nm.

ITU-T G.655 is a non-zero dispersion shifted fiber (NZDSF). Similar to G.653 fiber, this fiber was manufactured to have the dispersion shifted, not to 1550 nm, but outside of the C-band, either before or after. It's low attenuation and low dispersion at 1550 nm and works well with DWDM technology. This is considered the second most popular fiber type in the industry compared to G.652 fiber. The maximum chromatic dispersion coefficient of G.655 fiber for ~1550 nm is ±10 picosecond per nanometer kilometers.

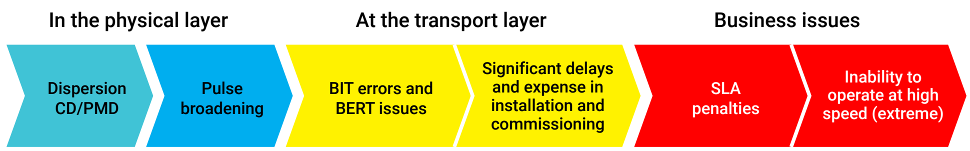
Similar to ITU-T G.655, there is **ITU-T G.656** fiber or low slope dispersion shifted fiber. This fiber has low dispersion over a longer wavelength range, typically from 1420 nm to 1600 nm. The problem with this fiber type is high cost so it is not very prevalent in the industry.

Inside multi-dwelling units (MDU) or in central offices, we can find **ITU-T G.657** bend insensitive fiber (BIF). The maximum chromatic dispersion coefficient of G.657 fiber for 1550 nm is 18.6 picosecond per nanometer kilometers.

An eye diagram is one of the best ways to characterize the quality of a link, or the clarity of a transmission.

Chromatic dispersion and its impact on data

For data rates less than 2.5 Gbit/s, chromatic dispersion has little impact on data flow. However, in today's environment, speed is everything. This is evident from subscribers demanding faster FTTH links, to 5G deployments for telehealth and autonomous vehicles, to the massive proliferation of data centers, and the fast-moving advancement of AI/ML. Moving from 25 Gbit/s to 100 Gbit/s and now onto 800 Gbit/s means that managing chromatic dispersion has become extremely important. When transmitting ones (laser on) and zeros (laser off) or bits, transmission is not just at one particular wavelength. It has a distribution of power versus wavelengths. Since wavelengths are not traveling at the same speed inside fiber, and blue being faster than red, at one point, there will be an overlap between the bits, which is called symbol interference, or inter-symbol interference.



Managing chromatic dispersion

Chromatic dispersion can significantly impact signal quality, especially in high-speed communication systems. There are several different ways to manage the impact of chromatic dispersion.

Dispersion compensator modules, compensation modules, DCM or DSEM are negative chromatic dispersion devices, which means that when a signal is broadened by chromatic dispersion, a negative chromatic dispersion is added to compress the pulse. This is mandatory for every span, even for signals that are very sensitive such as 2.5G, 10G, or everything that is not coherent.

A coherent system can filter the amount of chromatic dispersion, since it's linear, over a very long distance.

However, it is important to be careful if there is a mix of coherent and non-coherent transmitters. About 10 years ago, 10G and 100G signals were transmitted in the same fiber, and both weren't cohabiting well; the 10G signal was sensitive to chromatic dispersion and needed DCM compensators, while the coherent signal needed chromatic dispersion to function.

Non-coherent systems

Short distance or non-coherent transmitters, such as the ones deployed for 5G, remote PHY and FTTH, use non-return to zero (NRZ) amplitude modulation, as well as PAM-4. PAM-4 uses multiple amplitudes (i.e. not limited to zeros and ones). With this technology, more bits per symbol can be encoded, therefore transmit a higher bit rate. The problem when those transmitters are modulated is that they develop chirp. Chirping is a natural broadening of the signal as the laser signal is modulated. So, if a broader signal is inserted in a medium that is sensitive to speed versus wavelength chromatic dispersion, it will be even more sensitive to chromatic dispersion.

Modulated lasers are more sensitive to chromatic dispersion. It's important to identify the fiber type (i.e., CWDM, LAN WDM, or another). If it is supposed to be G.652 fiber, and it's a G.655 instead, the fiber will not support the transceivers. The chromatic dispersion would be highly negative, and the transmission won't work or will have a lot of errors. Not a desired effect in the context of 5G.

Coherent systems

It is important to note that transmitters are not coherent, receivers are. Here is how this type of systems works. For a given laser, both types of polarizations are split, and each arm is modulated with different phases, which is called a phase modulation, not amplitude. One signal is zero at 180 degrees, zero pi, and the other one is at 90 or 270 degrees. With a QPSK transmitter, there is dual polarization, quadratic (or quaternary) phase shifting (i.e., four streams in one laser). This needs to be detected at the end, on the receiver side. This is where the coherent detector comes into play. With a mix of phases here that are transmitted, there is a need to make a coherence or to correlate phases using a local oscillator. This local oscillator is a tunable laser that is tuned to the signal being transmitted (i.e., at the same wavelength). The digital processing (DSP) computes the transfer function of the signal, compensates for most problems on the link and identifies the phases from the different streams.

Non-linear effect

When coherent signals don't have enough (or any) chromatic dispersion, they create an electric field induced by the light itself and leads to nonlinear effects. When two signals are traveling in the same fiber at a certain level of power, you need a certain level of power to generate an electrostriction effect. This phenomenon is called the Kerr effect and results in modifying the index of refraction.

Without chromatic dispersion, wavelengths traveling together in the fiber disturb each other by passing on the same atoms at the same time over again. This induces a nonlinear effect. With chromatic dispersion, even if the signal or if the index of refraction is disturbed locally, it does not impact the other wavelength, because they do not travel through the same atoms at the same time.

The three biggest nonlinear effects on fiber in current systems are self-phase modulation, cross phase modulation, and four wave mixing. **Cross-phase modulation** causes phase modulation of the optical signal due to interactions between different channels within the same fiber. **Self-phase modulation** sees the phase of an optical pulse change as it propagates through the fiber, resulting in spectral broadening. **Four wave mixing** is when multiple optical signals overlap in the fiber, and generate new frequencies through nonlinear mixing.

Additional references

ITU-T G.650.3: Test methods for installed single-mode optical fibre cable links
www.itu.int/rec/T-REC-G.650.3-201708-I

Conclusion

While chromatic dispersion is a natural characteristic of optical fibers, in order to understand it's impact on the fiber link it must be measured thoroughly, as stipulated in ITU-T G.650.3. Chromatic dispersion is a linear phenomenon, and it increases proportionally with distance, meaning that 10 kilometers of G.652 fiber will have 170 picoseconds per nanometer of chromatic dispersion. **It is very easy to predict. Once the fiber is manufactured, chromatic dispersion will not change. Variation can happen with temperature, but often this variation is not noticeable.**

In short, chromatic dispersion cannot fail in the field, meaning that, when testing for chromatic dispersion and the value is beyond your threshold, the only way to fix the issue is to replace the fiber. **Chromatic dispersion is not a problem—it is a characteristic of the fiber.**

With testing, a compensation module can be accurately set by knowing the CD link value or the precise link length, which EXFO's FTBx-570 CD/PMD single-ended analyzer can provide in less than 30 seconds, from just one end of the fiber link.