SIGNAL DEGRADATION IN OPTICAL FIBERS

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Abstract
Dispersion is the spreading of a light pulse as it propagates down the fiber. Since optical fiber is a waveguide, light can propagate in a number of modes. If a fiber is of large diameter, light entering at different angles will excite different modes while narrow fiber may only excite one mode. Multimode propagation will cause dispersion, which results in the spreading of pulses and limits the usable bandwidth. Single-mode fiber has much less dispersion but is more expensive to produce. Its small size, together with the fact that its numerical aperture is smaller than that of multimode fiber, makes it more difficult to couple to light sources. Dispersion distorts both pulse and analog modulation signals.

Keywords: Modal Dispersion, Intramodal Dispersion or Chromatic Dispersion, Material Dispersion, Waveguide Dispersion

I. Introduction
Dispersion results when some components of the input signal spend more time traversing the fiber than other components. In a pulse modulated system, this causes the received pulse to be spread out over a longer period. It is noted that actually no power is lost to dispersion; the spreading effect reduces the peak power. In step-index fibers, the index of refraction changes radically between the core and the cladding. Graded-index fiber is a compromise multimode fiber, but the index of refraction gradually decreases away from the center of the core. Graded-index fiber has less dispersion than a multimode step-index fiber. Dispersion mechanisms within the fiber cause broadening of the transmitted light pulses as they travel along the channel. The phenomenon is illustrated in Figure (1) where it may be observed that each pulse broadens and overlaps with its neighbors, eventually becoming indistinguishable at the receiver input. The effect is known as inter symbol interference (ISI). The error rate is also a function of the signal attenuation on the link and the subsequent signal-to-noise ratio (SNR) at the receiver. For no overlapping of light pulses down on an optical fiber link the digital bit rate $B_T$ must be less than the reciprocal of the broadened (through dispersion) pulse duration ($2\tau$).

$$B_T \leq 1/2\tau$$

The maximum bit rate for an optical channel with dispersion may be obtained by considering the light pulses at the output to have a Gaussian shape with an rms width of $\sigma$.

$$B_T(\text{max}) = \frac{0.2}{\sigma} \text{bit s}^{-1}$$

Figure 1 : An illustration using the digital bit pattern 1011 of the broadening of light pulses as they are transmitted along a fiber: (a) fiber input; (b) fiber output at a distance $L_1$; (c) fiber output at a distance $L_2 > L_1$

Dispersion of optical energy within an optical fiber falls into following categories: Intermodal Delay or Modal Delay and Intramodal Dispersion or Chromatic Dispersion

1. Material Dispersion
2. Waveguide Dispersion
3. Polarization – Mode Dispersion
II. Modal (Intermodal Delay) Dispersion
The temporal spreading of a pulse in an optical waveguide caused by modal effects. Intermodal, or modal, dispersion occurs only in multimode fibers. Contributes to pulse broadening. Intermodal distortion or modal delay appears only in multimode fibers. This signal distortion mechanism is a result of each mode having a different value of the group velocity at a single frequency. The amount of spreading that occurs in a fiber is a function of the number of modes propagated by the fiber and length of the fiber. [1]

III. Intramodal Dispersion or Chromatic Dispersion:
Intramodal dispersion may occur in all types of optical fiber and results from the finite spectral line width of the optical source. Since optical sources do not emit just a single frequency but a band of frequencies, then there may be propagation delay differences between the different spectral components of the transmitted signal. The delay differences may be caused by the dispersive properties of the waveguide material (material dispersion) and also guidance effects within the fiber structure (waveguide dispersion). Intramodal dispersion depends on the wavelength, its effect on signal distortion increases with the spectral width of the light source. Spectral width is approximately 4 to 9 percent of a central wavelength. Intramodal Dispersion depends on the following three factors
1. Material dispersion
2. waveguide dispersion
3. Cross product dispersion

3.1 Material dispersion
Material dispersion occurs because the spreading of a light pulse is dependent on the wavelengths' interaction with the refractive index of the fiber core. Material dispersion is a function of the source spectral width, which specifies the range of wavelengths that can propagate in the fiber. Material dispersion is less at longer wavelengths. Pulse broadening due to material dispersion results from the different group velocities of the various spectral components launched into the fiber from the optical source. It occurs when the phase velocity of a plane wave propagating in the dielectric medium varies on linearly with wavelength, and a material is said to exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero i.e. $\frac{d^2 n}{d\lambda^2} \neq 0).$ [2]

The pulse spread due to material dispersion may be obtained by considering the group delay $\tau_g$ in the optical fiber which is the reciprocal of the group velocity $v_g$.

Hence the group delay is given by:

$$\tau_g = \frac{d\beta}{d\omega} = \frac{1}{c}\left(n_1 - \frac{\lambda}{c} \frac{d n_1}{d\lambda}\right)$$

Where $n_1$ is the refractive index of the core material. The pulse delay $\tau_m$ due to material dispersion in a fiber of length $L$ is therefore

$$\tau_m = \frac{L}{c}\left(n_1 - \frac{\lambda}{c} \frac{d n_1}{d\lambda}\right)$$

For a source with rms spectral width $\sigma_\lambda$ and a mean wavelength $\lambda$, the rms pulse broadening due to material dispersion $\sigma_m$ may be obtained from the
above expansion of Eq. in a Taylor series about \( \lambda \)
where:

\[
\sigma_m = \sigma_\lambda \frac{d^2 \tau_m}{d\lambda^2} + \ldots
\]

As the first term in Eq. (3) usually dominates, especially for sources operating over the 0.8 to 0.9 m wavelength range, then

\[
\sigma_m \approx \sigma_\lambda \frac{d \tau_m}{d\lambda}
\]

Hence the pulse spread may be evaluated by considering the dependence of \( \tau_m \) on \( \lambda \), where from Eq. (2):

\[
\frac{d \tau_m}{d\lambda} = \frac{L \lambda}{c} \left[ \frac{d n_0}{d\lambda} - \frac{d^2 n_1}{d\lambda^2} - \frac{d n_2}{d\lambda} \right]
\]

Therefore, substituting the expression obtained in Eq. (5) into Eq. (4), the rms pulse broadening due to material dispersion is given by:

\[
\sigma_m = \frac{\sigma_\lambda L}{c} \lambda \left| \frac{d^2 n_1}{d\lambda^2} \right|
\]

The material dispersion for optical fibers is sometimes quoted as a value for \( |\lambda/( d^2 n_1/d\lambda^2) | \) or simply \( | d^2 n_1/d\lambda^2 | \).

However, it may be given in terms of a material dispersion parameter \( M \) which is defined as:

\[
M = \frac{1}{L} \left| \frac{d \tau_m}{d\lambda} \right| = \frac{\lambda}{c} \left| d^2 n_1 \right| \left| \frac{d\lambda}{d\lambda^2} \right|
\]

and expressed in units of ps nm\(^{-1}\) km\(^{-1}\).

### Transmission characteristics of optical fibers

![Figure 3: The material dispersion parameter for silica as a function of wavelength](image)

#### 3.2 Waveguide dispersion

Waveguide dispersion occurs because the mode propagation constant is a function of the size of the fiber's core relative to the wavelength of operation. Waveguide dispersion also occurs because light propagates differently in the core than in the cladding.

Waveguide dispersion occurs when the speed of a wave in a waveguide, such as a coaxial cable or optical fiber depends on its frequency. This type of dispersion leads to signal degradation in telecommunications because the varying delay in arrival time between different components of a signal "smears out" the signal in time. It causes pulse spreading because only part of the optical power propagating along a fiber is confined to core. Dispersion arises because the fraction of light power propagating in the cladding travels faster than the light confined to core. The amount of waveguide dispersion depends on the fiber design. Single mode fiber confines only 80 percent of the power in the core for V values around 2.

Waveguide dispersion is due to the dependency of the group velocity of the fundamental mode as well as other modes on the V number. In order to calculate waveguide dispersion, we consider that \( n \) is not dependent on wavelength. Defining the normalized propagation constant \( b \) as:

\[
b = \frac{\beta^2}{k^2} - \frac{n_2^2}{n_1^2} \approx \frac{\beta}{k} - \frac{n_2}{n_1}
\]

solving for propagation constant:

\[
\beta \approx n_2 k (1 + b \Delta)
\]

Using V number

\[
V = ka(n_1^2 - n_2^2)^{1/2} \approx k a n_1 \sqrt{2 \Delta}
\]

Delay time due to waveguide dispersion can then be expressed as:

\[
\tau_{wg} = \frac{L}{n_2 + n_2 \Delta \frac{d(Vb)}{dV}}
\]

#### 3.3 Signal Distortion in single mode fibers
For single mode fibers, waveguide dispersion is in the same order of material dispersion. The pulse spread can be well approximated as

\[ \sigma_{wg} \approx \frac{d \sigma_{mc}}{d \lambda} = L \sigma_{mc} \left| \frac{d^2 \varphi}{d \lambda^2} \right| = \frac{n_2 L \Delta \sigma}{c \lambda} \frac{d^2 V_b}{d V^2} \]

### 3.4 Overall fiber dispersion

1. Multimode fibers:

The overall dispersion in multimode fibers comprises both chromatic and intermodal terms. The total rms pulse broadening \( \sigma_T \) is given by:

\[ \sigma_T = (\sigma_C^2 + \sigma_n^2)^{1/2} \]

Where \( \sigma_C \) is the intramodal or chromatic broadening and \( \sigma_n \) is the intermodal broadening caused by delay differences between the modes (i.e. \( \sigma_C \) for multimode step index fiber and \( \sigma_g \) for multimode graded index fiber).

The chromatic term \( \sigma_C \) consists of pulse broadening due to both material and waveguide dispersion. However, since waveguide dispersion is generally negligible compared with material dispersion in multimode fibers, then

\[ \sigma_C = \sigma_m \]

Total dispersion within single-mode fibers:

The total first-order dispersion \( DT \) in a practical single-mode fiber as comprising:

\[ DT = DM + DW + DP \] (ps nm\(^{-1}\) km\(^{-1}\))

which is simply the addition of the material dispersion \( DM \), the waveguide dispersion \( DW \) and the profile dispersion \( DP \) components. In standard single-mode fibers the total dispersion tends to be dominated by the material dispersion of fused silica.

**Transmission characteristics of optical fibers**

![Waveguide parameter](image)

![Material dispersion](image)

![Pulse dispersion](image)
and dotted curves) and the overall dispersion (solid curve).

### 3.5 The total chromatic dispersion:

The variation of the chromatic dispersion with wavelength is usually characterized by the second-order dispersion parameter or dispersion slope $S$ which may be written as:

$$ S = \frac{dD_T}{d\lambda} = \frac{d^2\tau_g}{d\lambda^2} $$

Whereas the first-order dispersion parameter $D_T$ may be seen to be related only to the second derivative of the propagation constant $\beta$ with respect to angular frequency the dispersion slope can be shown to be related to both the second and third derivatives.

$$ S = \frac{2\pi\alpha^2}{\lambda^4} \frac{d\beta}{d\phi^2} + \frac{4\pi\beta}{\lambda^5} \frac{d\beta}{d\phi^3} $$

Higher order chromatic effects impose limitations on the possible bandwidths that may be achieved with single-mode fibers. By contrast the minimum pulse spread at a wavelength of 0.85 m is around 100 ps nm$^{-1}$ km$^{-1}$. An important value of the dispersion slope $S(\lambda)$ is obtained at the wavelength of minimum chromatic dispersion $\lambda_0$ such that, $S_0 = S(\lambda_0)$. $S_0$ is called the zero-dispersion slope which is determined only by the third derivative of $\beta$. Typical values for the dispersion slope for standard single-mode fiber at $\lambda_0$ are in the region 0.085 to 0.095 ps nm$^{-1}$ km$^{-1}$.

[3]

The total chromatic dispersion at an arbitrary wavelength can be estimated when the two parameters $\lambda_0$ and $S_0$ are specified as:

$$ D_T(\lambda) = \frac{\lambda S_0}{4} \left[ 1 - \left( \frac{\lambda_0}{\lambda} \right)^4 \right] $$

### IV. Conclusion

Signal degradation in optical fibers due to dispersion is shown in this paper. Intermodal distortion or modal delay appears only in multimode fibers but Intramodal dispersion occurs in all types of optical fiber and results from the finite spectral line width of the optical source. Material dispersion caused by second differential of the refractive index with respect to wavelength is not zero i.e. $d^2n/d\lambda^2 \neq 0$). Waveguide dispersion occurs because light propagates differently in the core than in the cladding.

### References


