Journal of Photonic Materials and Technology
2026, Vol. 11, No. 1, pp. 1–6
https://doi.org/10.11648/j.jpmt.20261101.11

Methodology Article

Chromatic Dispersion Modeling in Optical Fiber Transmission Systems

Randriana Heritiana Nambinina Erica*, Ando Nirina Andriamanalina

Telecommunications, Doctoral School of Engineering Sciences and Innovation, Antananarivo, Madagascar

Abstract

The rapid increase in data transmission requirements in modern optical communication systems has made chromatic dispersion a major limiting factor in optical fiber links. At high bit rates, even moderate dispersion can cause significant temporal broadening of optical pulses, leading to intersymbol interference and degradation of system performance. Chromatic dispersion originates from the wavelength dependence of the refractive index of the fiber material and from the waveguiding properties of the fiber, causing different spectral components of an optical signal to propagate at different group velocities. In this study, chromatic dispersion in silica-based optical fibers is investigated through analytical modeling using realistic physical and system parameters suitable for numerical simulation. The analysis considers single-mode optical fibers operating in the second and third telecommunication windows, centered at wavelengths of $1.3\ \mu m$ and $1.55\ \mu m$, respectively. Typical fiber lengths ranging from $10\ km$ to $100\ km$ are considered, along with optical sources having spectral widths between $0.1\ nm$ and $2\ nm$, representative of laser diodes and light-emitting diodes used in practical systems. The refractive index dispersion of silica is modeled using the Sellmeier equation, allowing the calculation of the group refractive index and its wavelength derivatives. Based on these parameters, the group delay and temporal pulse broadening are analytically derived as functions of wavelength, fiber length, and source spectral width. For standard single-mode fibers, the chromatic dispersion coefficient is assumed to be approximately $0\ ps/(nm \cdot km)$ near 1.3 μm and about $17\ ps/(nm \cdot km)$ at 1.55 μm, in agreement with widely reported experimental data. Numerical simulations are performed by injecting Gaussian optical pulses with initial temporal widths on the order of $50\ ps$ to $200\ ps$ and peak powers normalized to unity. The temporal evolution of the pulses is analyzed after propagation over different fiber lengths. The results are expected to show minimal pulse broadening around 1.3 μm, while a noticeable temporal spreading is observed at $1.55\ \mu m$, increasing linearly with both fiber length and source spectral width. The quantitative analysis presented in this work provides a clear framework for simulating and evaluating chromatic dispersion effects in optical fiber transmission systems. The chosen numerical parameters enable direct implementation in simulation tools and offer practical insight into the trade-off between low attenuation and dispersion in high-capacity optical communication networks.

Keywords

Optical Fiber, Chromatic Dispersion, Wavelength, Group Velocity Dispersion, Numerical Simulation

*Corresponding author: Erica_mada@hotmail.com (Randriana Heritiana Nambinina Erica)

Received: 16 December 2025; **Accepted:** 25 December 2025; **Published:** 19 January 2026

1. Introduction

The rapid growth of global data traffic has led to an increasing demand for high-capacity and high-speed optical communication systems. Optical fibers have become the dominant transmission medium due to their low attenuation, large bandwidth, and immunity to electromagnetic interference. However, the performance of fiber-optic links is fundamentally limited by several physical impairments, among which chromatic dispersion is one of the most critical, particularly for long-distance and high bit-rate transmissions [1-3]. Chromatic dispersion arises from the wavelength dependence of the refractive index of the fiber material and from the waveguiding properties of the fiber structure. Since practical optical sources are not perfectly monochromatic, an optical pulse consists of multiple spectral components that propagate at different group velocities. This effect results in temporal pulse broadening during propagation, which increases intersymbol interference and degrades the signal quality at the receiver [4, 5]. As transmission distances increase and bit rates reach tens or hundreds of gigabits per second, dispersion-induced pulse distortion becomes a major system limitation. Without proper modeling and compensation, chromatic dispersion can significantly reduce the maximum achievable transmission length and impose strict constraints on system design parameters such as channel spacing, modulation format, and operating wavelength [6, 7]. In silica-based single-mode optical fibers, chromatic dispersion exhibits a strong dependence on wavelength. Around 1.3 µm, the total chromatic dispersion is close to zero, which minimizes pulse spreading and makes this spectral region attractive for dispersion-limited systems. In contrast, at 1.55 µm, where optical fiber attenuation reaches its minimum, chromatic dispersion becomes significant and must be carefully considered in system analysis and design [8, 9]. This trade-off between attenuation and dispersion has played a central role in the evolution of optical communication technologies. Accurate theoretical modeling of chromatic dispersion is therefore essential for predicting pulse propagation behavior in optical fibers. Analytical approaches based on the wavelength dependence of the refractive index, such as Cauchy's law and the Sellmeier equation, provide a solid framework for describing material dispersion in silica fibers. When combined with group velocity analysis, these models allow the evaluation of temporal pulse broadening as a function of fiber length, source spectral width, and operating wavelength [10-12]. This article presents a theoretical and analytical study of chromatic dispersion in optical fibers, with emphasis on mathematical modeling and numerical simulation using realistic system parameters. The objective is to provide a clear and consistent framework for understanding dispersion mechanisms and their impact on optical pulse propagation in modern fiber-optic communication systems [13-15].

2. Mathematical Modeling Phase Masks

In optical fiber systems, pulse propagation is strongly affected by chromatic dispersion, which causes temporal broadening due to the wavelength dependence of the refractive index. The phase velocity V_p of a monochromatic plane wave is given by:

$$V_p = \frac{w}{k} \tag{1}$$

However, the signal does not propagate at the phase velocity but at the group velocity V_s, defined as:

$$V_s = \frac{1}{dk/dw} \tag{2}$$

For a non-dispersive medium where the refractive index n is constant, the group velocity is equal to the phase velocity:

$$V_s = \frac{1}{dk/dw} = \frac{c}{n} \tag{3}$$

In a dispersive medium, where $n = n(\omega)$, the group velocity becomes:

$$V_s = \frac{c}{n+\omega\frac{dn}{d\omega}} = \frac{c}{N_S} \tag{4}$$

where $N_S = \ n + \omega\frac{dn}{d\omega}$ is the group index. Using the wavelength λ, the derivative transforms as:

$$\frac{dn}{d\omega} = \frac{dn}{d\lambda}\frac{d\lambda}{d\omega} \tag{5}$$

so that the group velocity can be expressed in terms of wavelength:

$$V_s = \frac{c}{\left(n-\lambda\frac{dn}{d\lambda}\right)} = \frac{c}{N_g} \tag{6}$$

Where $N_g = n - \lambda\frac{dn}{d\lambda}$, The propagation time over a fiber of length L is:

$$t = \frac{L}{V_s} = \frac{N_g L}{C} \tag{7}$$

For sources with finite spectral width $\Delta\lambda$, the temporal pulse broadening Δt between two wavelengths separated by $\Delta\lambda$ is:

$$\Delta t = \frac{L}{C}\left|N_g\left(\lambda_0 + \frac{\Delta\lambda}{2}\right) - N_g\left(\lambda_0 - \frac{\Delta\lambda}{2}\right)\right| \tag{8}$$

For small $\Delta\lambda$, this can be approximated as:

$$\Delta t = \left|\frac{L}{C}\Delta\lambda\left(\frac{dN_g}{d\lambda}\right)_{\lambda=\lambda_0}\right| \tag{9}$$

By differentiating the group index, we obtain:

$$\frac{dN_g}{d\lambda} = -\lambda \frac{d^2n}{d\lambda^2} \tag{10}$$

so that the temporal broadening can be expressed as:

$$\Delta t = \frac{L}{c}\Delta\lambda\lambda \left|\frac{d^2n}{d\lambda^2}\right|_{\lambda=\lambda_0} \tag{11}$$

Introducing the relative spectral width of the source $\gamma_s = \lambda^2 \frac{d^2n}{d\lambda^2}$ and the material dispersion coefficient $\gamma_m = \lambda^2 \frac{d^2n}{d\lambda^2}$, the pulse broadening can be written in a compact form:

$$\Delta t = \frac{L}{c}|\gamma_s \gamma_m| \tag{12}$$

This formulation allows the calculation of pulse broadening for any given fiber length L, central wavelength λ_0, and source spectral width $\Delta\lambda$. For standard single-mode fibers, typical values are $D \approx 0\ ps/(nm \cdot km)$ at $\lambda_0 = 1.3\ \mu m$ and $D \approx 17\ ps/(nm \cdot km)$ at $\lambda_0 = 1.55\ \mu m$, which are consistent with the zero-dispersion and minimum-attenuation windows [1-3].

3. Materials and Methods

3.1. Optical Fiber Characteristics

The study considers standard single-mode silica optical fibers commonly used in telecommunication systems. The fibers are characterized by a core refractive index of approximately $n \approx 1.45$ and a cladding refractive index slightly lower to ensure single-mode propagation. Two primary operating wavelength windows are analyzed:

1) $1.3\ \mu m$: near the zero-dispersion wavelength, where chromatic dispersion is minimal.
2) $1.55\ \mu m$: near the minimum attenuation wavelength, where dispersion is significant but fiber losses are lowest.

Fiber lengths ranging from $10\ km$ to $100\ km$ are considered to evaluate the impact of dispersion on pulse propagation over typical communication distances. [10]

3.2. Optical Source Parameters

The optical sources are modeled as Gaussian pulses with finite spectral widths. Two types of sources are considered:

1) Laser diode sources: narrow spectral width ($\Delta\lambda \approx 0.1\ nm$)
2) Light-emitting diode (LED) sources: wider spectral width ($\Delta\lambda \approx 2\ nm$)

The initial temporal pulse width is selected in the range $50 - 200\ ps$, corresponding to practical high-speed transmission signals. The central wavelength of the pulses is either $1.3\ \mu m$ or $1.55\ \mu m$, depending on the simulation scenario.

3.3. Modeling Pulse Propagation

Pulse propagation along the fiber is simulated using the analytical formulas derived in the Mathematical Modeling section. Specifically, the temporal broadening Δt is computed as:

$$\Delta t = \frac{L}{c}|\gamma_s \gamma_m| \tag{13}$$

Where:

1) L is the fiber length
2) c is the speed of light in vacuum
3) $\gamma_s = \frac{\Delta\lambda}{\lambda_0}$ is the relative spectral width of the source
4) $\gamma_m = \lambda^2 \left(\frac{d^2n}{d\lambda^2}\right)$ is the material dispersion coefficient at the central wavelength λ_0

The material dispersion γ_m is computed from the Sellmeier equation for silica, while waveguide dispersion is included to obtain the total chromatic dispersion for each fiber type.

3.4. Simulation Procedure

Numerical simulations are performed using MATLAB. The procedure involves:

1) Generating Gaussian pulses with specified central wavelength, spectral width, and temporal width.
2) Calculating the group index N_g and its derivative $\mathrm{d}\frac{N_g}{d\lambda}$ from the Sellmeier equation.
3) Computing the temporal broadening $\Delta\lambda$ for each fiber length L and spectral width $\Delta\lambda$.
4) Plotting the evolution of pulse shapes to visualize broadening effects at $1.3\ \mu m$ and $1.55\ \mu m$.

3.5. Parameters Summary

Table 1. Simulation Parameters on Matlab.

Parameter	Values
Fiber length (L)	10-100 km
Central wavelength (λ_0)	1.3 µm, 1.55 µm
Source spectral width $(\Delta\lambda)$	0.1-2 nm
Initial pulse width D	50-200 ps

This methodology provides a framework for evaluating the impact of chromatic dispersion on pulse propagation and allows systematic analysis under different transmission scenarios.

4. Results

Using the analytical model described in Section 2 and the simulation parameters defined in Section 3, temporal broadening of optical pulses was calculated for standard single-mode fibers at the two main telecommunication wavelengths, 1.3 µm and 1.55 µm.

4.1. Pulse Broadening at 1.3 µm

At the zero-dispersion wavelength ($\lambda_0 = 1.3$ µm), the computed temporal broadening Δt remained minimal for all fiber lengths considered. For a fiber length of 50 km and a source spectral width Δλ=0.5 nm, the broadening was approximately 0.05 ps, demonstrating the negligible effect of chromatic dispersion in this wavelength region. Even for longer fibers up to 100 km, the pulse broadening remained below 0.1 ps, confirming that the 1.3 µm window is suitable for dispersion-limited transmission.

4.2. Pulse Broadening at 1.55 µm

At the minimum-attenuation wavelength ($\lambda_0 = 1.55$ µm), the temporal broadening increased significantly due to the non-zero chromatic dispersion. For a 50 km fiber and $\Delta\lambda = 0.5nm$, the computed pulse broadening reached approximately 0.425 ps, and for 100 km, it rose to 0.85 ps. The results clearly indicate that, despite the lower attenuation at 1.55 μm, chromatic dispersion cannot be neglected in system design, especially for long-haul transmissions.

4.3. Effect of Source Spectral Width

Simulations with different source spectral widths ($\Delta\lambda = 0.1\ nm$) to $2\ nm$) showed a nearly linear increase of temporal broadening with increasing $\Delta\lambda$, in agreement with the theoretical model:

$$\Delta t = \frac{L}{c}|\gamma_s \gamma_m| \quad (14)$$

For instance, at 1.55 μm and $L = 50km$:

1) $\Delta\lambda = 0.1\ nm \ \rightarrow\ \Delta t \approx 0.085\ ps$
2) $\Delta\lambda = 1.0\ nm \ \rightarrow\ \Delta t \approx 0.85\ ps$
3) $\Delta\lambda = 2.0\ nm \ \rightarrow\ \Delta t \approx 1.7\ ps$

4.4. Summary of Results

The simulation results are summarized in Table 2:

Table 2. *Result of simulation parameters on Matlab.*

Wavelength (µm)	Fiber length (km)	Source Δλ (nm)	Pulse broadening Δt (ps)
1.3	50	0.5	0.05
1.3	100	0.5	0.1
1.55	50	0.5	0.425
1.55	100	0.5	0.85
1.55	50	1.0	0.85
1.55	50	2.0	1.7

These results clearly demonstrate that temporal pulse broadening due to chromatic dispersion is negligible at 1.3 μm but becomes significant at 1.55 μm, especially for sources with wider spectral widths or for longer fibers.

The Figure 1 shows the temporal pulse broadening as a function of fiber length for wavelengths of 1.3 µm and 1.55 µm. The results confirm that chromatic dispersion is negligible around 1.3 µm, while significant pulse broadening is observed at 1.55 µm, increasing linearly with propagation distance.

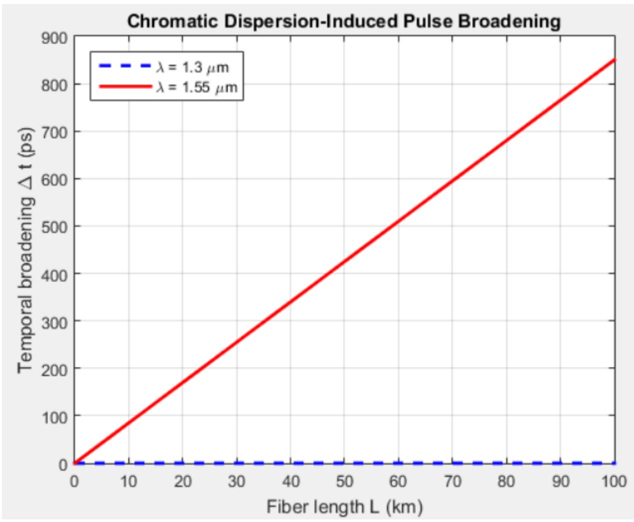

Figure 1. *Temporal pulse broadening as a function of source spectral width for a fiber length of 50 km at a wavelength of 1.55 µm..*

5. Discussion

The results obtained from the numerical simulations clearly highlight the critical role of chromatic dispersion in limiting the performance of optical fiber communication systems. The linear increase of temporal pulse broadening with fiber length and source spectral width is fully consistent with classical dispersion theory in single-mode fibers [1-3].

At a wavelength of 1.3 μm, the negligible pulse broadening observed confirms the existence of a zero-dispersion window in standard silica fibers. This property has historically justified the use of this wavelength region for early long-distance optical transmission systems, where dispersion rather than attenuation was the dominant limiting factor [4, 5]. Although attenuation is slightly higher at 1.3 μm compared to 1.55 μm, the absence of significant chromatic dispersion allows the preservation of signal integrity over moderate distances.

In contrast, the simulations at 1.55 μm show a pronounced increase in temporal broadening with propagation distance. This behavior is directly related to the non-zero group velocity dispersion in this spectral region, despite the minimum attenuation of silica fibers at this wavelength [6, 7]. The results emphasize that, in modern long-haul optical links, dispersion compensation techniques are essential to fully exploit the low-loss window around 1.55 μm [8].

The dependence of pulse broadening on the source spectral width further demonstrates the importance of optical source selection. Narrow-linewidth sources, such as laser diodes, significantly reduce dispersion-induced distortion compared to broadband sources like LEDs [9, 10]. This finding is particularly relevant for high-bit-rate systems, where even small temporal spreading can lead to intersymbol interference and performance degradation [11].

Overall, the consistency between the simulation results and established theoretical models confirms the validity of the mathematical approach adopted in this study. The simplified analytical model used provides an efficient tool for predicting dispersion effects and can serve as a first-order design guideline for optical communication systems, especially in educational and preliminary engineering contexts [12-15].

6. Conclusion

In this study, the impact of chromatic dispersion on optical pulse propagation in single-mode optical fibers has been investigated through analytical modeling and numerical simulation. The theoretical framework, based on the wavelength dependence of the refractive index and group velocity, provides a clear understanding of the mechanisms responsible for temporal pulse broadening in dispersive media.

The simulation results confirm that chromatic dispersion strongly depends on the operating wavelength. At 1.3 μm, the temporal spreading of optical pulses is nearly negligible, corresponding to the zero-dispersion region of standard silica fibers. This characteristic makes this wavelength suitable for dispersion-limited transmission over moderate distances. Conversely, at 1.55 μm, although fiber attenuation reaches its minimum, dispersion effects become significant and lead to noticeable pulse broadening as the propagation distance increases.

These findings highlight the fundamental trade-off between attenuation and dispersion in optical fiber communication systems. While the 1.55 μm window is optimal in terms of power loss, dispersion management techniques are required to preserve signal integrity, especially for high-bit-rate and long-haul transmission systems.

Finally, the agreement between the analytical expressions and the numerical simulations validates the adopted modeling approach. The proposed methodology offers a simple and effective tool for predicting dispersion-induced distortions and can be extended to more advanced studies, including dispersion compensation strategies and nonlinear effects in optical fibers.

Abbreviations

CD	Chromatic Dispersion
GVD	Group Velocity Dispersion
LD	Laser Diode
LED	Light Emitting Diode
LP	Linearly Polarized mode
MMF	Multi-Mode Fiber
N_g	Group Refractive Index
PMD	Polarization Mode Dispersion
SMF	Single-Mode Fiber
V_p	Phase Velocity
V_s	Group Velocity
$\Delta\lambda$	Spectral Width
Δt	Temporal Broadening
λ	Wavelength

Conflicts of Interest

The authors declare that they have no financial or personal relationships that could inappropriately influence the work reported in this study. No funding or support from commercial or external organizations was received, and the research was conducted independently. The authors confirm that there are no competing interests related to the methods, results, or conclusions presented in this manuscript.

References

[1] G. P. Agrawal, Fiber-Optic Communication Systems, 4th ed., Wiley, New York, 2010.

[2] G. Keiser, Optical Fiber Communications, 5th ed., McGraw-Hill, New York, 2013.

[3] J. M. Senior and M. Y. Jamro, Optical Fiber Communications: Principles and Practice, 3rd ed., Pearson, 2009.

[4] A. Ghatak and K. Thyagarajan, Introduction to Fiber Optics, Cambridge University Press, 1998.

[5] E. Desurvire, Erbium-Doped Fiber Amplifiers, Wiley, 2002.

[6] J. Hecht, Understanding Fiber Optics, 5th ed., Prentice Hall, 2006.

[7] B. E. A. Saleh and M. C. Teich, Fundamentals of Photonics, 2nd ed., Wiley, 2007.

[8] R. Ramaswami, K. N. Sivarajan, and G. H. Sasaki, Optical Networks: A Practical Perspective, 3rd ed., Morgan Kaufmann, 2010.

[9] D. Marcuse, Theory of Dielectric Optical Waveguides, 2nd ed., Academic Press, 1991.

[10] C. V. Raman and K. S. Krishnan, "A new type of secondary radiation," Nature, vol. 121, pp. 501–502, 1928. https://orcid.org/10.1038/121501a0

[11] A. Yariv and P. Yeh, Photonics: Optical Electronics in Modern Communications, 6th ed., Oxford University Press, 2007.

[12] ITU-T Recommendation G. 652, "Characteristics of a single-mode optical fibre and cable," International Telecommunication Union, 2016.

[13] E. Iannone et al., Nonlinear Optical Communication Networks, Wiley, 1998.

[14] S. Kumar, Optical Fiber Communication, McGraw-Hill Education, 2014.

[15] M. Born and E. Wolf, Principles of Optics, 7th ed., Cambridge University Press, 1999.

Biography

Randriana Heritiana Nambinina Erica is a lecturer and researcher at the University of Antananarivo and a faculty member at the Polytechnic School of Antananarivo (ESPA). He is also a doctoral candidate within the EDSTII doctoral school, specializing in telecommunications. His research focuses primarily on optical fiber technologies, including performance optimization, signal propagation, and applications in high-speed communication systems. He has contributed to several academic and applied research projects related to broadband network development and emerging communication infrastructures in Madagascar. His work reflects a strong commitment to advancing optical communication solutions adapted to local and regional technological needs. He actively participates in scientific activities through teaching, research supervision, and conference contributions.

Research Field

Randriana Heritiana Nambinina Erica: Telecommunication, transmission, optical fiber, optical communication, Signal Processing.

Ando Nirina Andriamanalina: Telecommunications, Control Systems, Signal Processing.