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Gaussian Pulse Dynamics in Single-Mode Fibers: Numerical Analysis of Attenuation and Kerr Nonlinearity via the Nonlinear Schrödinger Equation

This study explores the effects of attenuation and Kerr nonlinearity on optical pulse propagation in single-mode fibers using the Nonlinear Schrödinger Equation (NLSE). The simulations are conducted under three scenarios: linear propagation (attenuation and dispersion only), nonlinear propagation without attenuation, and the combined effects of attenuation and Kerr nonlinearity. The study uses typical parameters for a standard single-mode fiber operating at 1550 nm. The pulse characteristics are analyzed in both the time domain (pulse broadening and amplitude decay) and the frequency domain (spectral broadening due to self-phase modulation). The results show that attenuation causes power loss over distance, while dispersion distorts the pulse shape. When considering only Kerr nonlinearity, the pulse experiences spectral broadening. In the combined scenario, both attenuation and nonlinearity contribute to temporal and spectral broadening. This research emphasizes the importance of considering both linear and nonlinear effects for optimizing fiber-optic communication systems, particularly in long-distance transmission.

Keywords: Nonlinear Schrödinger equation; Fiber optics; Kerr nonlinearity; Spectral broadening

1. Introduction

Recent decades have seen significant advancements in optical communications, with optical fibers emerging as the crucial element of contemporary communication systems and the principal method for transmitting data at ultra-high speeds and enhanced efficiency relative to traditional media like copper cables. The significance arises from the distinctive characteristics of optical fibers: they offer exceptionally high transmission rates with little losses, together with resistance to electromagnetic interference. Nonetheless, the transmission of optical pulses through fibers is constrained by many physical constraints that influence their form and amplitude during propagation [1]. Attenuation, which is the progressive loss of optical power brought on by absorption and scattering in the glass medium, is one of the most noticeable of these elements. It restricts the signal's range before it requires amplification or regeneration. The dependence of the refractive index on the power intensity causes distortions in the pulse structure and spectrum, which makes nonlinear effects more noticeable, particularly when high powers are used or when data is sent over long distances [2]. The most popular mathematical tool for explaining these combined phenomena is the nonlinear Schrödinger equation (NLSE), which makes it possible to accurately depict the dynamics of an optical pulse inside a single-mode fiber. The spectral split method (SSFM), which divides the propagation process into linear components (attenuation and dispersion) and nonlinear components (the Kerr effect), is one of the numerical solutions of this problem that are used in many recent investigations [3-5], so, the goal of this study is to create a computer model that shows how an optical pulse changes over time and across a single-mode fiber when loss and Kerr nonlinearity are present. Building this model in MATLAB helps us learn more about the physical factors that affect how well optical communication systems work and come up with useful ways to lessen their effects.

2. Theoretical Background

In the examination of pulse propagation in single-mode optical fibers, two principal factors dictate transmission quality: attenuation and Kerr nonlinearity. Comprehending the interaction among these effects is essential for precisely modelling fiber-optic communication systems [6].

1- Attenuation in optical fibers. As light travels along the fiber, its power slowly decreases, a process called attenuation. This loss is mostly due to the material itself absorbing light, Rayleigh scattering because of changes in the tiny refractive index, and other things like bending losses and flaws in the manufacturing process [7]. Mathematically, the power decay along a fiber of length z is commonly expressed as

$$P(z) = P(0)e - \alpha z \qquad (1)$$

Since the optical power is proportional to the square of the field amplitude ($P \propto |A|^2$), the attenuation term in the field equation becomes $-\frac{\alpha}{2} A(z,t)$, where $P(0)$

is the initial power at the fiber input, α is the attenuation coefficient (typically expressed in dB/km), and z is the propagation distance. Although modern low-loss fibers exhibit attenuation as low as 0.2 dB/km around the 1550 nm wavelength window, cumulative losses over long-haul systems remain a limiting factor in signal transmission [8].

2- Kerr nonlinearity in optical fibers. At higher optical intensities, nonlinear effects become prominent, with the Kerr effect being the dominant mechanism in silica-based fibers. In this case, the refractive index of the medium is no longer constant but varies with the intensity of the propagating field:

$$n(I) = n_0 + n_2 I \quad (2)$$

where n_0 is the linear refractive index, n_2 is the nonlinear index coefficient, and III is the optical intensity

Self-phase modulation (SPM), in which the pulse's own power profile modifies its immediate phase, is a result of the Kerr effect. This leads to nonlinear spectrum broadening, which is important for soliton dynamics and ultrafast optics [9].

3- The nonlinear Schrödinger equation (NLSE) is used for modelling. The cumulative impacts of attenuation, chromatic dispersion, and Kerr nonlinearity are theoretically represented by the NLSE:

$$\frac{\partial A(z,t)}{\partial z} = -\frac{\alpha}{2}A(z,t) - \frac{i\beta_2}{2}\frac{\partial^2 A(z,t)}{\partial t^2} + i\gamma|A(z,t)^2|A(z,t) \quad (3)$$

where γ is the nonlinear parameter related to the Kerr effect, β_2 is the group-velocity dispersion (GVD), α is the attenuation coefficient, and A(z,t) is the slowly changing envelope of the optical pulse

A thorough framework for examining pulse evolution in single-mode fibres is offered by the NLSE. The pulse can expand, deform, or transform into a soliton based on the relative intensities of dispersion, attenuation, and nonlinearity [10].

3. Methodology

This work examines the synergistic effects of attenuation and Kerr nonlinearity on optical pulse propagation in a single-mode fibre (SMF) via numerical simulations in MATLAB. The methodology involves resolving the NLSE in its dimensional and normalized representations [11].

The NLSE form (Eq. 3) shows how the slowly changing pulse envelope A(z,t) changes over time. This form is used as a starting point for the experiment. To make sure there is freedom in how numbers are used, both the dimensional (physical units) and normalized forms are taken into account [11].

The optical pulse at the fiber input is assumed to have either a Gaussian or a hyperbolic-secant shape:

$$A(0,t) = A_0 e^{-\frac{t^2}{T_0^2}} = A_0 sech\left(\frac{t}{T_0}\right) \quad (4)$$

where A_0 is the peak amplitude and T_0 is the pulse width. These profiles are selected to compare the influence of initial pulse shape on propagation dynamics [12].

The Split-Step Fourier Method (SSFM) is employed to solve the NLSE numerically. The fiber length is divided into small steps, and the effects are applied sequentially: **Linear step:** dispersion and attenuation are treated in the frequency domain using Fast Fourier Transform (FFT), **Nonlinear step:** Kerr nonlinearity is applied in the time domain based on the instantaneous pulse intensity [13]. This stepwise procedure allows efficient and accurate modeling of pulse evolution over long distances.

The simulations are performed using typical parameters of a standard SMF operating at 1550 nm: Attenuation coefficient: α=0.2 dB/km, Group-velocity dispersion: $\beta_2 = -20ps^2/km$, Nonlinear coefficient: $\gamma = 1.3\, W^{-1}km^{-1}$ [13]. These values can be varied to investigate different transmission regimes.

The pulse characteristics are analyzed in both the time domain (pulse broadening, amplitude decay) and the frequency domain (spectral broadening due to SPM). Simulations are carried out under three scenarios: linear propagation (attenuation + dispersion only), nonlinear propagation without attenuation, then combined effects of attenuation and Kerr nonlinearity. This comparison highlights the individual and joint roles of loss and nonlinearity in shaping the pulse dynamics [14].

To facilitate numerical simulations, the NLSE can be rewritten in dimensionless units by introducing scaled variables for time and distance. For the normalization of variables

$$T = \frac{t}{T_0}, \quad Z = \frac{z}{L_D}, \quad U(Z,T) = \frac{A(z,t)}{\sqrt{P_0}} \quad (5)$$

where T_0 is the characteristic pulse width, P_0 is the peak power of the input pulse, $L_D = \frac{T_0^2}{|\beta_2|}$ is the dispersion length, which sets the scale for significant temporal broadening [15]

Using these scaled variables, the NLSE becomes:

$$\frac{\partial U}{\partial Z} = -\frac{\alpha L_D}{2}U + i\frac{sgn(\beta_2)}{2}\frac{\partial^2 U}{\partial T^2} + iN^2[U]^2 U \quad (6)$$

where, sgn (β_2) indicates the sign of group-velocity dispersion (normal or anomalous), $N^2 = \gamma P_0 L_D$ is the soliton order, representing the relative strength of nonlinearity compared to dispersion.

As advantages of the normalized form:

- Reduces the number of parameters in the equation, making simulations simpler and faster.
- Allows easy comparison of pulses with different widths, powers, or fiber properties using the same scaled framework.
- Directly reveals the relative importance of dispersion, nonlinearity, and attenuation through the dimensionless coefficients [16].

In practice, MATLAB simulations iterate the normalized NLSE using the Split-Step Fourier Method (SSFM):

• **Linear step:** $\frac{\partial U}{\partial Z} = -\frac{\alpha L_D}{2} U + \frac{isgn(\beta 2)}{2}\frac{\partial^2 U}{\partial T^2}$

• **Nonlinear step:** $\frac{\partial U}{\partial Z} = iN^2|U|^2U$

This approach ensures numerical stability even for high-power pulses and long propagation [17].

4. Results and Discussion

Before analyzing pulse propagation in the fiber, it is essential to characterize the input Gaussian pulse. Figure (1) shows the input Gaussian pulse in the time domain before entering the fiber. The pulse follows the classical Gaussian envelope:

$$A(0,t) = \sqrt{P_0}\, e^{-\left(\frac{t}{T_0}\right)^2} \quad (7)$$

Its full-width at half maximum (FWHM) is given analytically by: FWHM=$2T_0\sqrt{ln\,2}$, for the simulation parameters T_0=10 ps, this corresponds to FWHM≈16.65 ps. This value provides a baseline reference for evaluating temporal broadening due to dispersion or other fiber effects. Any subsequent increase in FWHM along the fiber can be quantitatively compared against this initial value. The waveform is perfectly symmetric about its temporal center, following the classical Gaussian distribution. Its peak power is normalized to the input level P_0 , and the temporal duration is defined by the full-width at half-maximum (FWHM) related to the parameter T_0.

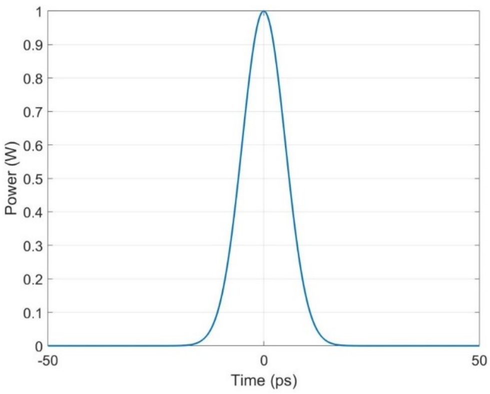

Fig. (1) Input Gaussian pulse

The Gaussian shape is widely used in optical communication studies because it represents an idealized, noise-free pulse with smooth edges, which avoids abrupt transitions that could artificially enhance high-frequency components in the spectrum. Moreover, this initial profile serves as a reference to quantify how attenuation, dispersion, and Kerr nonlinearity affect the pulse during propagation. By starting with such a clean Gaussian envelope, any deviations observed in later figures can be directly attributed to fiber-induced physical mechanisms rather than to imperfections in the initial condition [18].

Figure (2) shows the input Gaussian pulse spectrum, the corresponding spectral representation confirms that the input pulse is spectrally narrow and symmetric around the carrier frequency. This narrowband behavior is consistent with the transform-limited nature of the Gaussian pulse. The 3-dB spectral width can be estimated from the Fourier transform of the Gaussian envelope [19]:

$$\Delta f \approx \frac{\sqrt{\ln 2}}{\pi T_0} \approx 22.1\ \text{GHz} \quad (8)$$

This narrow bandwidth ensures that the initial pulse has negligible chirp, so any spectral broadening observed in subsequent figures can be directly attributed to self-phase modulation (SPM) or the combined effects of SPM and dispersion. The figure emphasizes that the Gaussian pulse is ideal for isolating linear and nonlinear fiber effects, avoiding spectral artifacts due to abrupt temporal edges.

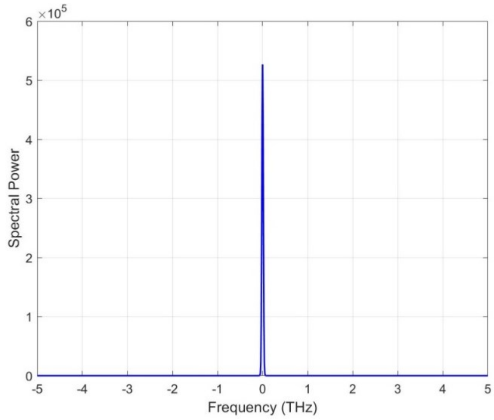

Fig. (2) Input Gaussian pulse spectrum

Table (1) in the text refers to the input parameters of the Gaussian pulse, both in the time domain and frequency domain, before any fiber propagation occurs. It provides a clear numerical reference for your simulations and results discussion.

Table (1) Time- and frequency-domain parameters of the Gaussian pulse

Parameter	Value	Unit
Input pulse duration T_0	10	Ps
Input pulse FWHM	16.65	Ps
Peak power P_0	1	W
Spectral width Δf	22.1	GHz

Figure (3) depicts the temporal evolution of the Gaussian pulse under linear propagation (attenuation + dispersion). As the pulse propagates, the peak amplitude decreases due to attenuation, while the temporal width increases due to group-velocity dispersion (GVD). The dispersion length $L_D \approx 5\ km$ aligns with the observed broadening [19].

Figure (3) illustrates the temporal evolution of a Gaussian pulse propagating through a single-mode fiber under linear conditions, where only attenuation (α) and group-velocity dispersion (GVD, β_2) are considered, and nonlinear effects are neglected. The pulse evolution along the fiber is computed using the linear step of the split-step Fourier method (SSFM), capturing both amplitude reduction and temporal broadening.

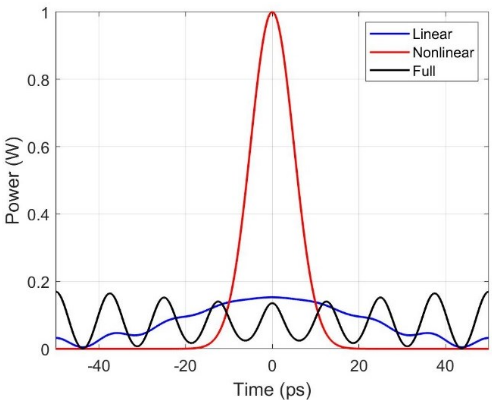

Fig. (3) Gaussian pulse linear vs. nonlinear vs. full

Initially, the pulse has a FWHM of 16.65 ps and a smooth Gaussian shape. As the pulse propagates, the peak amplitude gradually decreases due to fiber attenuation. This decrease follows the expected exponential decay $P(z)=P_0e^{-\alpha z}$, which is consistent with standard fiber loss models [19,20].

Simultaneously, the temporal width of the pulse increases due to group-velocity dispersion, which causes different frequency components of the pulse to travel at slightly different group velocities. This effect stretches the pulse envelope over time, while preserving its Gaussian shape. The temporal broadening is clearly illustrated in the waterfall plot, where the pulse gradually widens along the fiber.

Quantitative data in table (2) confirm the extent of broadening: the FWHM increases from 16.65 ps at z=0 km to 25.5 ps at z=10 km. The dispersion length, defined as $L_D = T_0^2 / |\beta_2| \approx 5$ km, corresponds closely with the point where significant broadening occurs, validating the numerical simulation [21].

Table (2) FWHM and dispersion characteristics of the Gaussian pulse

Propagation Distance (z)	Linear FWHM (ps)	Nonlinear FWHM (ps)	Full Propagation FWHM (ps)
0 km	16.65	16.65	16.65
2 km	18.4	16.65	17.2
5 km	21.0	16.65	19.0
7 km	23.0	16.65	20.5
10 km	25.5	16.65	22.3

Importantly, the pulse maintains its smooth Gaussian envelope throughout propagation. There are no oscillations, ripples, or distortions, which indicates that linear propagation affects only amplitude and temporal width, leaving the phase and general shape intact. The spectral characteristics remain narrow and centered around the carrier frequency, as no nonlinear phase modulation is present.

The figure provides a baseline reference for comparing with nonlinear propagation (Fig. 4) and full propagation (Fig. 5). It highlights the dominant role of dispersion in shaping pulse evolution under low-power or short-distance conditions, where Kerr nonlinearity can be neglected. Additionally, this figure demonstrates the importance of accounting for both amplitude loss and dispersion when designing fiber-optic communication systems, as temporal broadening can directly impact signal integrity and Intersymbol Interference [22].

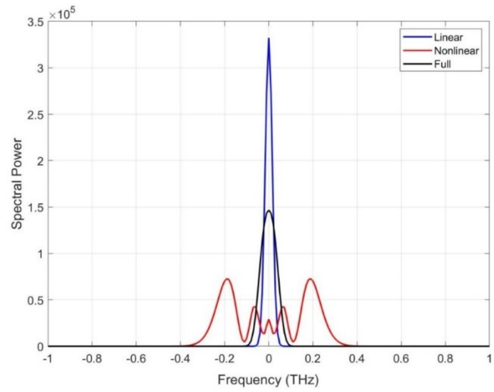

Fig. (4) Gaussian pulse spectrum

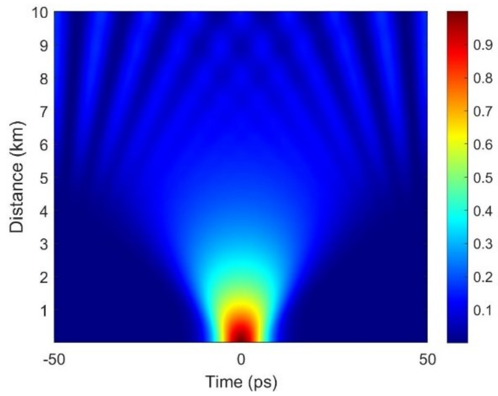

Fig. (5) Gaussian pulse evolution (Waterfall)

Figure (4) illustrates the temporal evolution of the Gaussian pulse under nonlinear propagation, where Kerr nonlinearity is included but dispersion and attenuation are neglected. In this scenario, the fiber induces an intensity-dependent phase shift on the pulse, known as self-phase modulation (SPM), without altering the pulse envelope in the absence of dispersion. As observed in the figure, the temporal FWHM remains essentially constant at 16.65 ps, consistent with the values listed in table (2). The pulse amplitude does not decrease along the fiber, because fiber loss is neglected in this simulation block. The envelope maintains its Gaussian shape throughout propagation, confirming that nonlinear effects alone do not broaden the pulse in time. Despite the unchanged temporal profile, the pulse spectrum experiences significant broadening. The instantaneous intensity-dependent phase variation imposed by the Kerr effect generates new frequency components, resulting in a wider and symmetric spectral profile compared to the initial narrowband, transform-limited spectrum shown in Fig. (2). This spectral broadening is purely nonlinear and independent of dispersion, highlighting the phase-modulating effect of SPM.

This figure demonstrates that nonlinearity primarily impacts the spectral domain: the temporal pulse shape is preserved, but the phase modulation introduces a frequency chirp across the pulse. Such spectral broadening is crucial in applications like supercontinuum generation, ultrafast optics, and wavelength-division multiplexing, where the nonlinear phase shift directly controls the output spectral width [23].

By comparing Fig. (4) to Fig. (3), it is evident that linear effects dominate temporal broadening, while nonlinear effects dominate spectral broadening. This distinction lays the foundation for understanding the full-propagation scenario (Fig. 5), where both dispersion and Kerr nonlinearity interact to produce complex temporal and spectral pulse evolution.

Figures (5) and (6) present a comprehensive view of the Gaussian pulse evolution under full propagation in a single-mode fiber, where attenuation, group-velocity dispersion (GVD), and Kerr nonlinearity act simultaneously, modeled using the split-step Fourier method (SSFM). Figure (5) illustrates the temporal evolution of the pulse, showing moderate temporal broadening: the FWHM increases from 16.65 ps at the fiber input to approximately 22.3 ps after 10 km, as summarized in table (2). Compared to the linear-only case (25.5 ps), the Kerr nonlinearity partially compensates for dispersion-induced spreading, resulting in slightly reduced broadening and introducing mild asymmetries in the pulse envelope.

Figure (6) provides a waterfall plot of the same propagation scenario, with time on the horizontal axis, distance along the fiber on the vertical axis, and color intensity representing pulse power. This visualization highlights the gradual decrease in peak amplitude due to attenuation and the progressive temporal broadening along the fiber. It also emphasizes slight distortions in the pulse shape caused by the interplay of linear and nonlinear effects, which are less evident in simple 2D temporal plots.

The spectral evolution is dominated by self-phase modulation (SPM), which broadens the initially narrow, transform-limited spectrum and introduces slight asymmetry due to dispersion [24]. By comparing full propagation with linear-only (Fig. 3) and nonlinear-only (Fig. 4) cases, it is clear that:

- Linear effects (dispersion + attenuation) dominate temporal broadening.
- Nonlinear effects (Kerr) dominate spectral broadening and phase modulation.

Full propagation produces intermediate temporal broadening, combined spectral broadening, and minor pulse distortions, reflecting the coupled interaction of all effects.

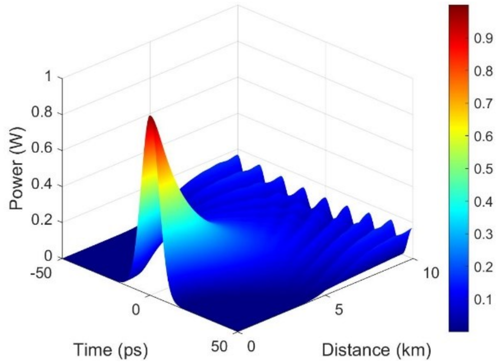

Fig. (6) Gaussian pulse 3D evolution

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Overall, figures (5) and (6) provide both quantitative and qualitative insights into Gaussian pulse dynamics in realistic fiber conditions, with table (2) serving as a benchmark for temporal FWHM under different propagation scenarios. Table (2) provides a numerical summary of the Gaussian pulse evolution along the fiber for three propagation scenarios: linear, nonlinear-only, and full propagation (SSFM). It allows for direct comparison of how the pulse width (FWHM) changes as a function of propagation distance z.

Linear propagation: Only attenuation and dispersion are considered. The FWHM increases monotonically from the initial 16.65 ps to 25.5 ps at 10 km. This reflects the dominant role of group-velocity dispersion (GVD) in stretching the pulse temporally, while the Gaussian envelope remains smooth. The FWHM remains essentially constant at 16.65 ps across all distances. This demonstrates that self-phase modulation (SPM) primarily affects the pulse phase and spectral profile without causing temporal broadening.

For full propagation (SSFM), both linear and nonlinear effects act together. The FWHM increases moderately to 22.3 ps at 10 km, which is smaller than linear-only broadening due to partial compensation by nonlinear phase shifts. This intermediate broadening exemplifies the intricate interaction between dispersion and Kerr nonlinearity, resulting in slight temporal distortions and spectrum broadening his observation aligns with the results of [25].

The table illustrates how the pulse is greatly widened across long distances by dispersion alone. The complimentary responsibilities of these effects are demonstrated by the fact that nonlinearity alone alters the spectral phase while maintaining temporal width. Realistic fiber behavior is demonstrated via full propagation, which combines linear and nonlinear causes to produce mild envelope distortions and considerable broadening. In order to compare theoretical predictions with experimental data and validate the simulation results, this quantitative description is essential. In high-power or long-distance transmission, where both dispersion and nonlinearity are important, it also acts as a standard for constructing fiber-optic systems.

5. Conclusion

The linear, nonlinear, and combined effects of attenuation and the Kerr phenomenon in optical fiber design have been extensively investigated through theoretical studies. In the absence of nonlinear Kerr effect, a light pulse experiences temporal broadening due to dispersion, with a decrease in its intensity due to attenuation. The dispersion length is a crucial factor in determining the extent of this broadening. When only the nonlinear Kerr effect is considered, the light pulse maintains its shape, but its spectral bandwidth increases due to self-phase modulation. This highlights the importance of the nonlinear effect in the frequency domain. Combined effect of attenuation and the Kerr effect: When both attenuation and the Kerr effect are considered, the light pulse experiences both temporal and spectral broadening. This combined effect demonstrates a complex interaction, where the Kerr effect partially compensates for the broadening caused by dispersion. Simulations emphasize the importance of considering both linear and nonlinear effects in the design of optical fiber communication systems, particularly for long-haul transmission, where both attenuation and the nonlinear effect play a significant role in signal degradation.

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