

Soliton For Optical Sensor: Numerical Studies

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ABSTRACT

Soliton for optical sensors is essentially a new way for overcoming a sensing sensitivity constraint. High sensitivity in terms of device accuracy is in demand nowadays, and it plays an important part in achieving improved performance. Due to this constraint, we observe that the largest sensing limitation originates from the input optical pulse that travels inside the waveguide, which governs pulse reduction before sensor testing. As a result, the development of optical soliton is required to circumvent this limitation. In the present work, we proposed design recommendations for soliton-based optical sensors by numerically investigating soliton production in a silicon channel waveguide. The effects of nonlinearity, dispersion, and waveguide geometry on soliton stability were examined. The findings indicate that adjusting the waveguide thickness to 300 nm guarantees single-mode operation at 1.55 μm , resulting in an anomalous dispersion regime with group velocity dispersion of $-26.83 \text{ ps}^2 \cdot \text{mm}^{-1}$ and a group index of 6.96. Stable solitary pulse propagation was made possible by the calculated soliton order of 0.84, which indicates operation near the basic soliton regime. At waveguide length of 8.7 mm, where dispersive and nonlinear effects are well balanced, maximum transmission took place, but soliton production required a minimum length of $\sim 4.5 \text{ mm}$. At this length, the soliton retained its intensity and pulse waveform, indicating strong propagation conditions. These findings provide a mathematical framework for connecting soliton order, dispersion length, and nonlinear length to sensor performance. The findings show that maintaining pristine soliton output within a silicon waveguide is a straightforward strategy to improve the sensitivity as well as performance of next-generation optical sensors.

Keywords: Optical soliton; Optical sensor; Nonlinear optical pulses, Silicon waveguide.

Nomenclature (Greek symbols towards the end)

L	Optimum waveguide length (m)
t	Time (s)
P_o	Optical Power (W)
T_o	Pulse Width (s)
γ	Nonlinear Coefficient ($\text{W}^{-1}\text{m}^{-1}$)
n_{Si}	Silicon Refractive Index (RIU)
A_{eff}	Effective Core Area (m^2)
Δz	Length of Segment (m)
ω	Frequency in The Fourier Domain (Hz)
β_2	Group Velocity Dispersion Coefficient ($\text{ps}^2 \text{ mm}^{-1}$)
n_2	Nonlinear Index (m^2W^{-1})
L_D	Dispersion Length (m)
L_N	Nonlinear Length (m)
λ	Wavelength (m)
D	Total dispersion ($\text{ps nm}^{-1} \text{ km}^{-1}$)
$\hat{D}$	Dispersion operator (m^{-1})
$\hat{N}$	Nonlinear operator (m^{-1})
E	Amplitude pulse
z	Location point (m)
$\exp$	Exponential function
i	Imaginary unit ($i = \sqrt{-1}$)
sech	Hyperbolic secant function
η	Segment number
n	Type of operator
$\partial/\partial t^2$	Differential operator for time domain

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$\partial/\partial z$	Differential operator for space domain
α	Optical loss (dBcm ⁻¹)
P	Output power (W)
$\bar{P}_o$	Average input power (W)

Abbreviations

GVD	Group Velocity Dispersion
SSFM	Split-Step Fourier Method
NLSE	Nonlinear Schrödinger Equation
SPM	Self-Phase Modulation

1.0 INTRODUCTION

Solitons, a fascinating occurrence in optics, have transformed the way information is transferred and processed [1]. Prior to the discovery of solitons, information in optical communication was limited by variables including dispersion and nonlinearity. Solitons, or self-reinforcing wave packets, have emerged as a powerful remedy to these restrictions [2]. The transformation and motion of solitons are described by nonlinear equations of mathematical physics [3-10]. These equations allow solitons to maintain their shape and amplitude as they propagate through a medium, enabling long-distance transmission of data without distortion. Since then, the study of solitons has expanded to various fields, including optics, where they have found wide-ranging applications in fiber-optic communications systems [11], optical data processing [12,13], and nonlinear optics [14-16].

Because of their capability to maintain waveform structure, solitons have also received attention in recent years for optical sensing applications, where they offer potential to identify subtle changes in the environment [17-20]. Observing the behaviour of optical solitons as they move through various sensing platforms, in particular how dispersion and nonlinear effects change the soliton profile, has been the main focus of the majority of prior studies. However, there is still a significant problem: because soliton amplitude and shape changes during transmission degrade the signal-to-noise ratio, widen detection responses, and impair measurement accuracy, they directly lower sensor sensitivity. Therefore, to achieve solid and high-resolution sensing, it is essential to make sure that a pristine soliton pulse forms before it begins interaction with the sensing medium. The development of a numerical method to maximize soliton production in a silicon channel waveguide for sensing applications is what makes this work novel. Here, we systematically identify the ideal waveguide length required to produce a pure solitary pulse before it enters the detecting zone, in contrast to earlier research that looked at soliton propagation in fibers or documented qualitative soliton behaviour in sensors. In order to enhance device sensitivity and reduce distortion during sensing, we make sure the soliton is fully formed at the input stage. This strategy provides a clear relationship between soliton dynamics and sensor performance, opening the door to the design of soliton-based sensors with increased stability and accuracy.

In this work, we aim to develop and create a soliton pulse inside a silicon channel waveguide ($n = 3.48$ [21-22]) using numerical analysis. To find the proper propagation distance for soliton generation, the study starts by finding the dispersion and nonlinear lengths. The formation of a steady solitary pulse is then guaranteed by optimizing other physical parameters including effective mode area, GVD, and soliton order. This method yields a useful framework for developing optical sensors based on soliton that improved both sensitivity and performance.

2.0 OPTICAL SOLITON DEVELOPMENT

Before executing the experiment, a mathematical model is used to predict if optical soliton can be created or not. Matlab executes the model's results. Figure 1 displays the creation of optical soliton pulses within a waveguide before they reach the sensing medium. Figure 1 also depicts a purple waveguide, which is engaged in optical soliton formation. An input optical pulse shape for this investigation begins with a bell shape, which is written as [20];

$$E(t) = \sqrt{P_o} \operatorname{sech}\left(\frac{t}{T_o}\right). \quad (1)$$

Here, the pulse amplitude and width are represented as $\sqrt{P_o}$ and T_o . Optical pulse when propagating along waveguide is governed by two effects known as a nonlinear and dispersion effect, respectively.

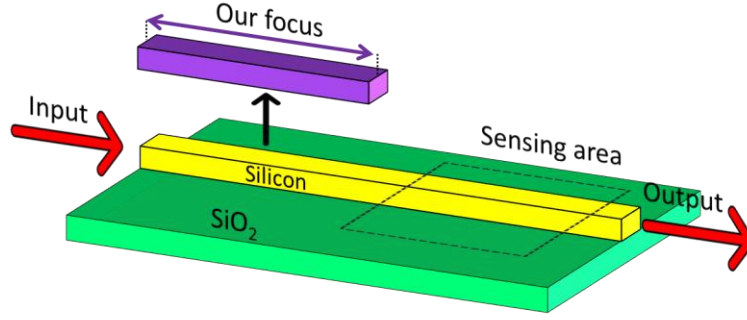


Figure 1. Illustration of the optical soliton pulse generation within sensing device.

A Split-Step Fourier Method (SSFM) is used to describe how these effects interact with the optical pulse. Agrawal developed the approach to demonstrate the interplay between these two effects in optical fiber [23, 24]. This method was also implemented by Yin *et al.* to study a soliton formation within waveguide [25]. The advantage of employing this technique is that it takes less time to create results and is the simplest split step scheme in which the calculation only involves first-order differential equations [26]. The technique is based on splitting the nonlinear Schrödinger equation (NLSE) into two parts, one of which describes group velocity dispersion (GVD), also known as the dispersion effect, and the other of which describes self-phase modulation (SPM), also known as the nonlinear effect, when a single pulse propagates through a waveguide. The technique starts by using NLSE as

$$i \frac{\partial E}{\partial z} + \left(\frac{\beta_2}{2} \right) \frac{\partial^2 E}{\partial t^2} + \gamma |E|^2 E = 0. \quad (2)$$

This equation depicts an interplay between dispersion and nonlinearity towards optical pulse within waveguide. The physical parameters within NLSE are the amplitude pulse, E , group velocity dispersion coefficient (GVD), β_2 , and nonlinear coefficient, γ , respectively. The coefficient of GVD and nonlinear have a relation with a dispersion and nonlinear length that are expressed by [21];

$$L_D = T_o^2 / |\beta_2| \quad (3)$$

$$L_N = (\gamma P_o)^{-1} \quad (4)$$

The NLSE from Equation (2) is deviated into two parts; dispersion $\hat{D}$ and nonlinear $\hat{N}$ parts as,

$$\frac{\partial E}{\partial z} = (\hat{D} + \hat{N}) E. \quad (5)$$

Here the operator of dispersion, $\hat{D}$, and nonlinear, $\hat{N}$, are expressed as,

$$\hat{D} = -i \frac{\beta_2}{2} \frac{\partial^2}{\partial t^2}, \quad (6)$$

$$\hat{N} = i\gamma P_o. \quad (7)$$

The amplitude of the pulse, $|E|^2$, is equal to the input optical power, P_o , demonstrating that the nonlinearity inside the medium is influenced by the optical field's input power. The Fourier transform technique is used to replace the differential operator $\partial/\partial t^2$ into $i^2\omega^2$ and ω is the frequency in the Fourier domain. Therefore, the equation is rewritten as

$$\hat{D} = \frac{i\beta_2\omega^2}{2}. \quad (8)$$

The dispersion operator account for GVD and nonlinear operator account for the effect of waveguide SPM on pulse propagation. There are two steps of propagation; the first step is pure dispersion and after that pure nonlinearity. The pure dispersion and nonlinear are expressed in differential equation,

$$\frac{\partial E}{\partial z} = \hat{D} \cdot E, \quad (9)$$

$$\frac{\partial E}{\partial z} = \hat{N} \cdot E. \quad (10)$$

The Equation (9) and (10) are solved as

$$E_{\hat{D}} = E \cdot \exp(\hat{D} \cdot z), \quad (11)$$

$$E_{\hat{N}} = E \cdot \exp(\hat{N} \cdot z). \quad (12)$$

Here the solution of $E_n = E \cdot \exp(n \cdot z)$ where n is represented as the dispersion and nonlinear operator basically described as a pulse propagation inside waveguide which includes the effect of dispersion and nonlinear. The split-step Fourier method is the technique used to obtain an approximate solution by considering the dispersion and nonlinearity are pretended to act independently. The work is extended by modeling the pulse propagation along waveguide in a small distance that called as the segment of length, Δz as shown in Figure 2. The Δz is selected in order to obtain a balance between efficiency and accuracy. The relationship between dispersion and nonlinearity is precisely addressed at each propagation step by setting Δz to be at least one to two orders of magnitude less than the shortest characteristic length for numerical stability [27]. This method minimizes processing overhead while ensuring steady simulation performance [28].

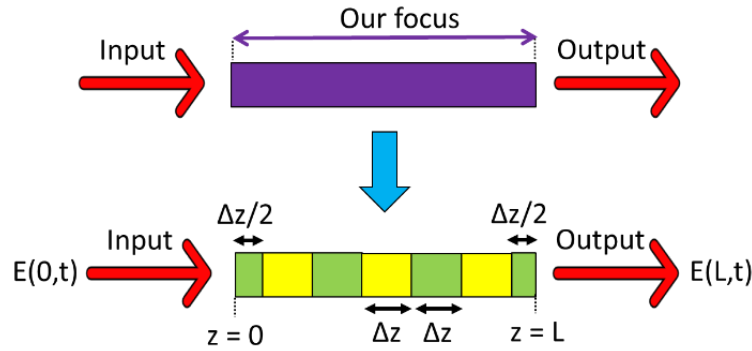


Figure 2. Illustration of the Split-step Fourier method in waveguide. The nonlinear effect (green) is included at side by side with dispersion effect as shown by a yellow colour.

Optical pulse propagation within waveguide represents as red arrow started by injecting the pulse at input port. The first effect influencing the pulse is the nonlinear effect. After that, the pulse continues to propagate into dispersion region. This process is repeated until pulse reaches at the end of the waveguide. Mathematically, the pulse propagation along medium can be described as

$$E(L,t) = \left[\exp(\hat{D} \cdot \Delta z) \cdot \exp(\hat{N} \cdot \Delta z) \dots \exp(\hat{D} \cdot \Delta z) \right] \cdot E(0,t) \quad (13)$$

with the length of segment, Δz , for channel waveguide is given by

$$\Delta z = \frac{L}{\eta} \quad (14)$$

Here, the L and η are the length of channel waveguide and number of the segment. Based on Equation 13, the interplay between dispersion and nonlinear effect of pulse propagation along medium is shown. To help understand more on the optical soliton formation via channel waveguide, Figure 3 presents a detailed flow chart that shows how the soliton pulse is formed based on the interaction between dispersion and a nonlinear. The flowchart outlines the numerical process employed to use the split-step Fourier method (SSFM) to model soliton production. The basic soliton shape is represented by a secant hyperbolic profile, which defines the initial input

pulse used in the simulation. Next, in the following steps along the propagation distance, nonlinear and dispersive effects are applied alternately to calculate the pulse propagation. To account for the intensity-dependent refractive index contribution, the nonlinear operator is applied across a half-step, given as $\exp(0.5 \cdot N \cdot \Delta z)$. The dispersion operator, $\exp(D \cdot \Delta z)$, which controls how group velocity dispersion (GVD) affects the pulse, comes next. To finish the propagation step, a second nonlinear half-step, $\exp(0.5 \cdot N \cdot \Delta z)$, is applied. This sequence is iteratively repeated over the appropriate number of propagation steps to ensure an accurate representation of the interplay between nonlinearity and dispersion. The repeated approach eventually leads to a stable solution in which dispersive spreading is precisely balanced by nonlinear self-phase modulation, resulting in the development of a soliton. This simulation's results match the conditions required for soliton formation and give a framework for studying pulse dynamics in nonlinear optical waveguides.

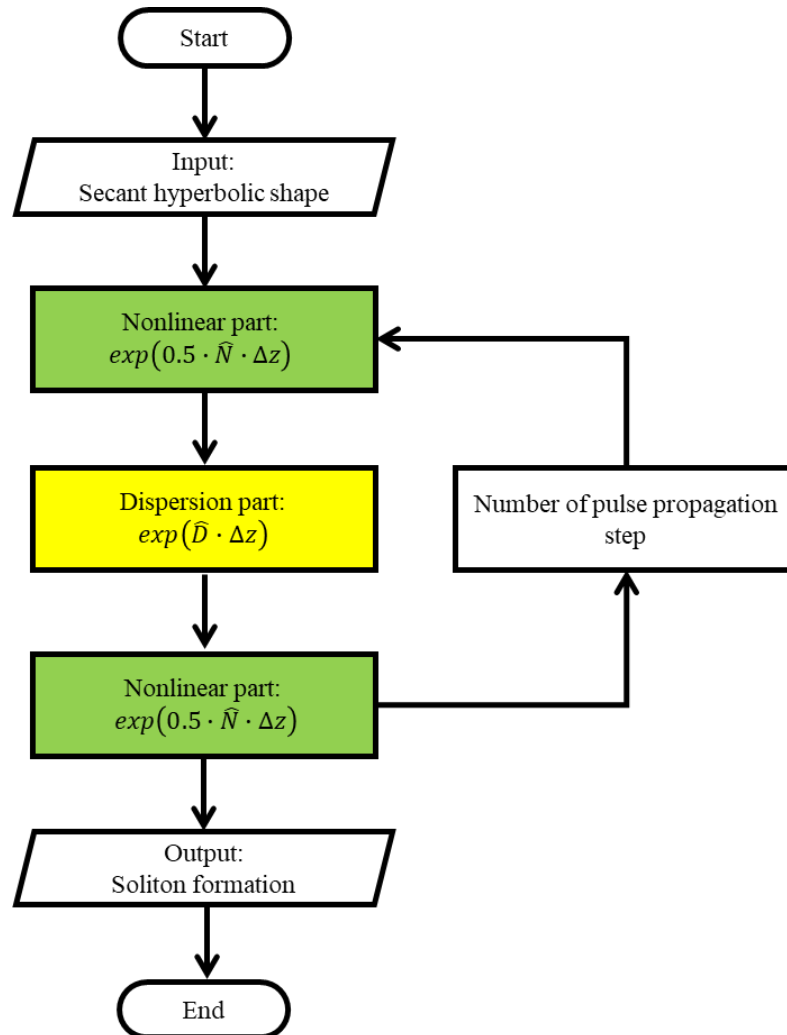


Figure 3. The split-step Fourier technique (SSFM) flowchart for modeling soliton generation. The nonlinear and dispersion effect are displayed by green and yellow colour respectively.

3.0 RESULTS AND DISCUSSION

In the previous topic, a mathematical description was created to get an expected outcome of the soliton pulse in waveguide. After that a numerical calculation took place for presenting a result of the pulse propagation along medium. To obtain an accurate result for sensing, input optical pulse should be in solitary wave or another word to describe a stability of optical pulse known as optical soliton. Optical soliton is a special phenomenon in light propagation along medium because its specialty to preserve its shape when propagate along medium.

Optical soliton propagation within a waveguide requires numerous characteristics, which are described in Figures 4 and 5. The optical parameters utilized in simulation are shown in Table 1. Here, the input power value was set by 1 W because the objective is to produce a high quantity of nonlinear coefficient, wherein their method to compute the precise value is given as $\gamma = 2\pi n_2 / \lambda \cdot A_{eff}$ [30]. The pulse width of 10 ps was chosen because it can reduce the dispersion effect within the waveguide [31]. The nonlinear effect depends on the nonlinear index in waveguide core. This effect can be increased by changing the silicon to other material with higher nonlinearity or use an intense light source. Another way to achieve high nonlinearity in waveguide is using smaller core area as depicted in Figure 4. It shows that smaller core area generates higher nonlinearity. Important notes from Foster *et al.* stated that if the core area is too small and approximate to zero, the nonlinearity suddenly drops to zero nonlinearity because mostly too small core area makes light propagate at cladding [32].

Table 1: Values of the parameters used for simulation of channel waveguide

Parameter	Symbol	Value	Reference
Nonlinear index	n_2	$6 \times 10^{-18} \text{ m}^2 \text{W}^{-1}$	[22]
Wavelength	λ	$1.55 \text{ } \mu\text{m}$	[22]
Effective mode area	A_{eff}	$0.13 \text{ } \mu\text{m}^2$	[29]
Nonlinear coefficient	γ	$187.09 \text{ W}^{-1} \text{m}^{-1}$	
Pulse width	T_o	10 ps	
Input peak power	P_o	1 W	
Core index	n_{Si}	3.48	[21,22]

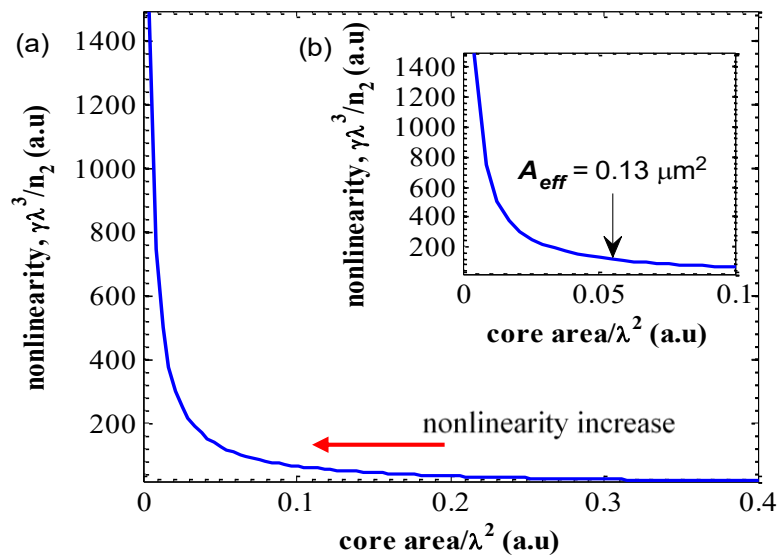


Figure 4. (a) Nonlinearity as a function of core area of a silicon waveguide.
(b) The core area of the waveguide used.

Unlike the dispersion effect, the effect is dependent on waveguide thickness. Waveguide thickness must be tailored to get the lowest possible dispersion effect. A single mode condition is required to achieve lower dispersion within a waveguide. In order to produce a single mode of $m = 1$ at a telecommunication wavelength of $1.55 \mu\text{m}$, the channel waveguide thickness should be between 295 and 300 nm. This research took a 300 nm channel waveguide thickness to achieve a single mode condition of 1 at a wavelength of $1.55 \mu\text{m}$ [see to Figure 5(a)]. Single mode development in a waveguide affects the magnitude of the group refractive index, resulting in a group index of 6.96 when the mode is 1. This group index value resulted in a total dispersion of $21.06 \text{ ps nm}^{-1} \text{ km}^{-1}$, as illustrated in Figure 5(b). The value of total dispersion created an abnormal dispersion regime, resulting in a negative group velocity dispersion coefficient of $-26.83 \text{ ps}^2 \text{ mm}^{-1}$. This regime describes the conditions required for soliton creation within a waveguide and is related to the soliton order N . The soliton order can be divided into two parts: fundamental and high-order soliton. The basic soliton ($N = 1$) is defined as the ideal condition for the pulse to retain its shape and amplitude [24]. For high-order soliton ($N \gg 1$), the pulse form and amplitude constantly vary periodically when propagating along the waveguide [23, 24]. Figure 5(c) shows that the soliton order was 0.84 (this value appears when we round the actual number of soliton order of 0.8358), which is still within the range of optical soliton conditions (0.5-1.5) for producing an optical single pulse [23, 24]. The significant magnitude of the soliton order of 0.84 signifies that a balance between dispersion and nonlinear impact has been achieved.

Finding the optimal length for producing a clean soliton pulse is what we want to accomplish after determining the precise value of soliton order. This waveguide's sufficient length must be greater than the nonlinearity and dispersion lengths. We changed the soliton order expression from $N = \sqrt{L_D/L_N}$ [35] to $N \cdot L_N = L_D/N$, where L_N and L_D stand for the nonlinear and dispersion lengths, respectively, in order to get the correct length. We successfully generated a minimal ideal length expression based on the derivation of the soliton order, which can be applied under two conditions: either refer to the nonlinear length, $L = N \cdot L_N$, or the dispersion length, $L = L_D/N$. Using $N = 0.8358$, $L_N = 5.34 \text{ mm}$, and $L_D = 3.73 \text{ mm}$, we determined the waveguide length, where both lengths yielded the same result of 4.5 mm. Our calculation indicated that this waveguide length is a minimum need for producing a soliton pulse, even if it is still within the dispersion region ($L > L_D$).

To follow the soliton requirement ($L > L_D = L_N$), we obtained an average output power along the waveguide using average input power $\bar{P}_o = L^{-1} \int_0^L P_o(L) dL$ [33] where the input power in this research refers to $P_o(L) = P/\exp(-\alpha L)$. The average input power result is then put into the soliton order formula as $\bar{P}_o = N^2/\gamma L_D$ [33]. $P = [(\alpha L/\gamma L_D) \cdot e^{(-\alpha L)}] N^2$ is the result for output power in this case, where $\alpha = 5 \text{ dBcm}^{-1}$ [32], γ , L_D , and N stand for optical loss, nonlinear coefficient, dispersion length, and soliton order, respectively. Based on the determined output power, Figure 6 displays the transmission variation (dB) as a function of waveguide length. At first, the transmission grew with length, reaching its peak at about $L = 8.7 \text{ mm}$, where $N = 0.84$ was the appropriate soliton order. The group velocity dispersion (GVD) and nonlinear effects were almost balanced at this length, resulting in a maximum transmission of roughly -4 dB . The transmission stayed relatively low for shorter lengths ($< 5 \text{ mm}$) because there is not enough nonlinear interaction length for soliton production and stabilization. Higher transmission arises from the pulse's larger nonlinear phase modulation as its length increases, which counters the dispersive broadening. The ideal situation, where dispersion and nonlinearity are balanced, is indicated by the transmission peak. After the ideal length ($> 8.7 \text{ mm}$), the transmission gradually started loss of efficiency. This reduction is related to the dominance of dispersive effects, which lead to pulse broadening and lower confinement within the waveguide. That means the overall transmission efficiency decreases as the soliton-like propagation weakens. The system appears to operate very close to the fundamental soliton regime ($N \approx 1$), as indicated by the reported soliton order $N = 0.84$. Even though it is not a perfect soliton, the transmission boost at this point shows that the device may be able to effectively utilize the interplay between dispersive and nonlinear effects to improve performance at specific lengths. Our results are in good agreement with previous studies according to the parameters of the ideal length required to produce optical soliton, and further investigation is being carried out by comparing our results with actual findings [34].

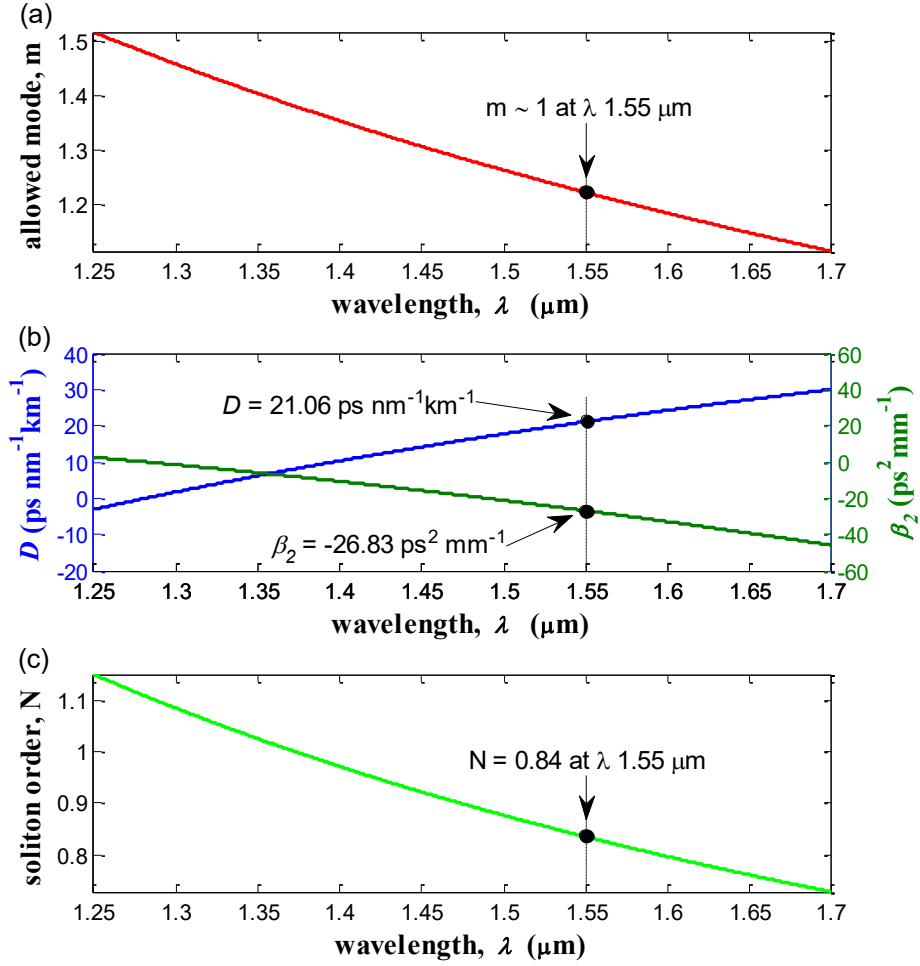


Figure 5. Simulation result of (a) allowed mode in waveguide core, (b) total dispersion and group velocity dispersion coefficient, and (c) soliton order against wavelength in near-infrared region.

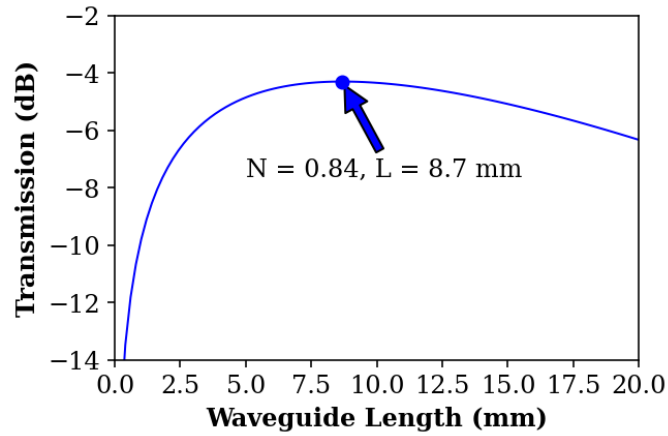


Figure 6. Simulation result of transimission against waveguide length.

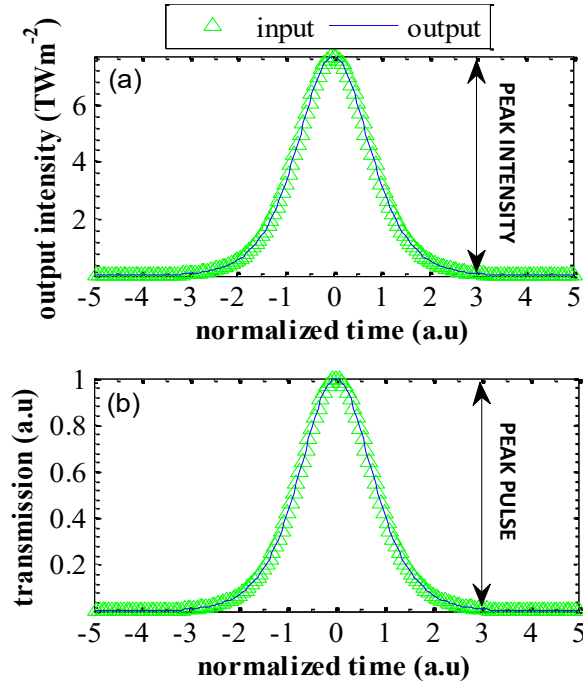


Figure 7. Soliton pulse generation along channel waveguide. (a) Result for output intensity as a function of normalized time and (b) result for transmission as a function of normalized time.

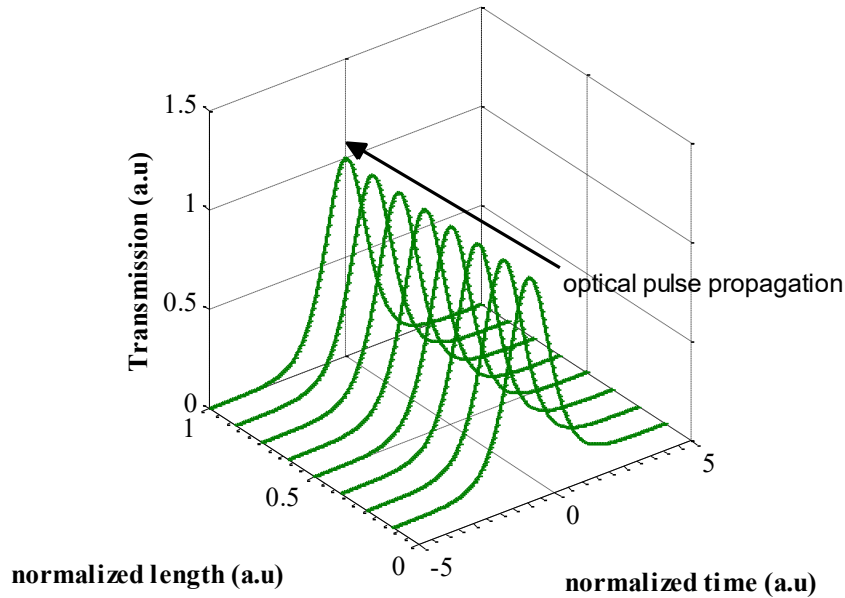


Figure 8. Optical soliton propagation along channel waveguide.

Figure 7 displays the intensity and pulse profile of soliton generation in a 1 Watt channel with a peak intensity of 7.7 TWm^{-2} and a core modal area of $0.13 \mu\text{m}^2$. The requirement for soliton production demonstrates that the intensity (peak intensity) and shape remain constant as they propagate along the channel waveguide. Figure 8 depicts another observation proving optical soliton propagation within a channel waveguide, which supports the findings in Figure 7. It depicts how a pulse keeps its shape as it travels through a waveguide. This soliton production result inside a silicon waveguide is consistent with other research that has shown a similar soliton wave pattern when it enters a waveguide [36].

4.0 CONCLUSION

In order to maximize its application in optical sensing, this work numerically investigated the necessary conditions for soliton formation in a silicon channel waveguide. We showed that soliton stability is highly dependent on waveguide geometry and propagation length by looking at the interaction between dispersion and nonlinear effects. While the single-mode condition at 1.55 μm was obtained by adjusting the waveguide thickness to 300 nm, resulting in an anomalous dispersion regime ($\beta_2 = -26.83 \text{ ps}^2 \cdot \text{mm}^{-1}$) and a group index of 6.96, it was demonstrated that nonlinearity increased with reduced core area or higher input intensity. Dispersion and nonlinear effects are almost balanced in the fundamental soliton domain, which is confirmed by the soliton order of $N = 0.84$. This led us to determine the minimum propagation length needed for soliton generation, and we discovered that the highest transmission happens at $\sim 8.7 \text{ mm}$, while the threshold for solitary pulse formation is $\sim 4.5 \text{ mm}$. The soliton maintains its intensity and pulse profile at this ideal length, indicating steady propagation inside the waveguide. These findings offer a quantitative foundation for the design of soliton-based optical sensors, where maintaining soliton integrity is crucial for accuracy and sensitivity. The method creates clear design guidelines that relate nonlinear length, dispersion length, and soliton order to practical device performance. Future research will experimentally validate these findings and expand the method to include other high-nonlinearity materials that will boost sensor performance.

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AUTHORS CONTRIBUTION

Azam Mohamad: Formal analysis, Investigation, writing original draft
 Mohamad Helmi Abd Mubin: Conceptualization, Methodology, writing -Review and editing
 Siti Azwani Yacoob: Formal analysis, Investigation
 Muhammad Sufi Roslan: Introduction and Literature review
 Munzir Abdullah: Validation and Conceptualization

DECLARATION OF COMPETING OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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