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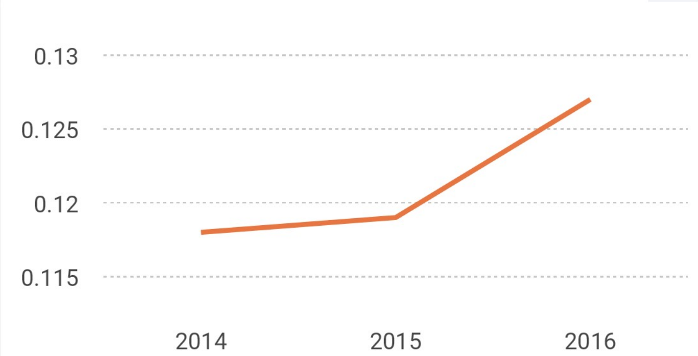

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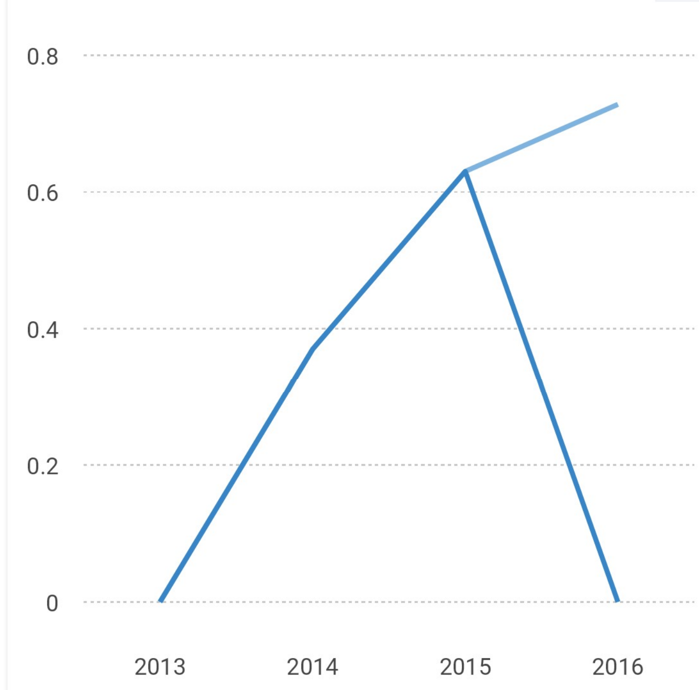

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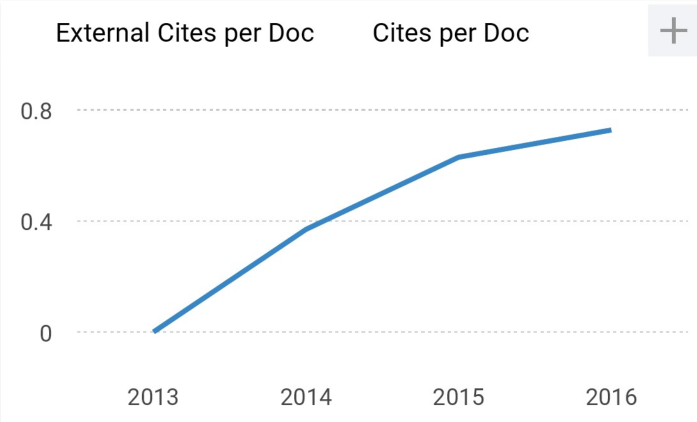

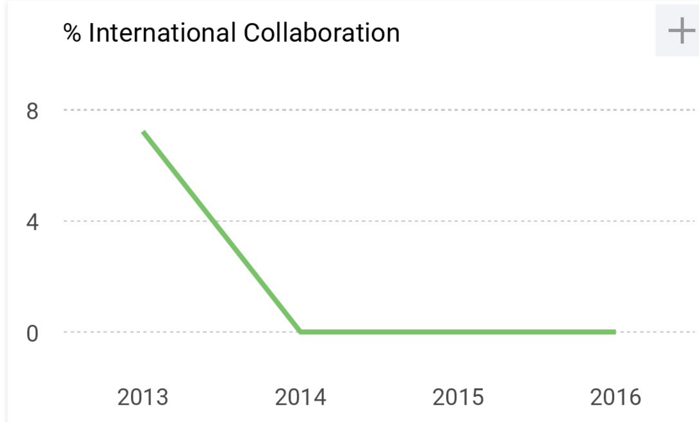

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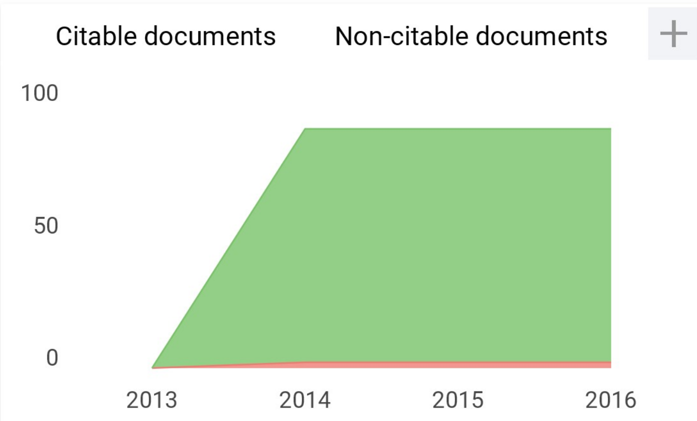

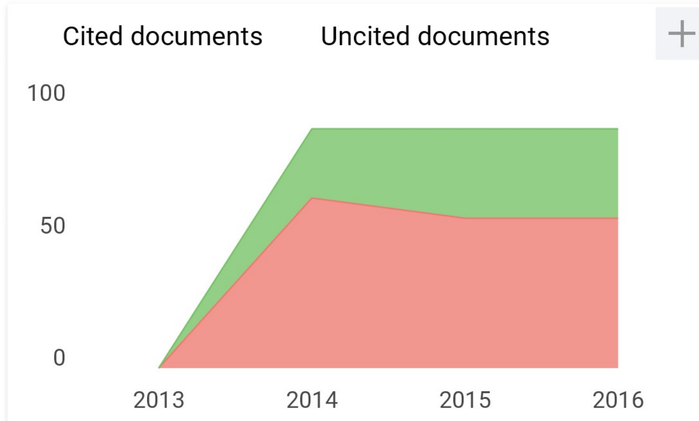

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Phone/Fax: +628157002232
E-mail: atwbox@gmail.com

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Dark and Bright Soliton in Fiber Optics

Subekti Ari Santoso[1)], Fakhrurrozi[1)], Octarina Nur S[1)]
[1)] Departement of Electrical Engineering, Faculty of Science and Technology, University of Al Azhar Indonesia
Jakarta, Indonesia
e-mail : subektiari@gmail.com

Ary Syahriar[1)2)]
[2)]Agency for The Assessment and Application of Technology
Jakarta, Indonesia
e-mail : ary@uai.ac.id

***Abstract* – Nonlinear Schrödinger equation is a general form for modeling and explaining the phenomenon of nonlinear physics system. Nonlinear Schrödinger Equation (NSE) describes the propagation of light pulses that are stable in Kerr medium. This paper discusses the analytic formulation of nonlinear Schrödinger equation which is influenced by Stimulated Raman Scattering and Self Steepening derived from Maxwell's equations. The NSE equation is also influenced by the linear response of a dielectric material and nonlinear dielectric response. The propagation profile of pulse soliton is stable and this is suitable to be implemented in optical communication to carry the information.**

Keywords — Nonlinear Schrödinger Equation, Self Steepening, Stimulated Raman Scattering, Maxwell Equation, Soliton.

I. INTRODUCTION

The discovery of laser technology in early 1960s stimulates many researchers to conduct the experiments especially in the application of fiber optic. Fiber optic cables have the capability to carry data with large capacity and high speed [1]. However, fiber optic has many losses when it is transmitted for long distances communication. Then the experiment is also developed in investigating the light source with high intensity which allows the transmission of information. Recently, several researches have been developed to apply the nonlinear waves (soliton) in optical communications to carry the information [2].

The modern development of the soliton theory in the last three decades of the 20th century has lead to a number of important applications and developments in several areas of contemporary physics and mathematics [3]. The soliton was first observed by Russell as surface waves in 1834 [4]. Theoretical explanation of the experimental Russell is obtained from the experimental work of Korteweg and de Vries [4] - [8], which found the *Koteweg-de Vries equation (KdV)*. This is a partial differential equation whose solution describes the existence of soliton [8].

Soliton is the result of the removal of nonlinear effect from a medium with the same medium dispersion effect [9]. The effect of dispersion occurs because light wave propagates at different speeds due to different frequencies [10], thus widening the pulse wave. This effect is called *Group Velocity Dispersion (GVD)*. However, to maintain a pulse, it uses nonlinear effect of fiber-optic called *Self Phase Modulation (SPM)* [11].

Soliton propagation tends to be stable and has been developed for applications in optical communications with high speed access [4]. In the field of optical communications, the information signal is modulated in a pulse light and transmitted in fiber optic based on the principle of Total Internal Reflection [12].

Soliton has great potential to be applied in optical communications; this encourages the development of research to investigate the characteristic of soliton. This paper investigates the characteristics of soliton especially for bright and dark soliton. This paper discusses the Nonlinear Schrödinger equations derived from Maxwell's equation which is including the perturbation factor : *Self steepening (SS), Stimulated Raman Scattering (SRS)* and *Thrid Order Dispersion (TOD).* Then the soliton equation is simulated numerically using MATLAB. The characteristic of soliton is investigated by changing the value of parameter β and δ , which are the parameter of the group velocity dispersion. The simulation result is expected to describe about the characteristics of bright and dark soliton which can be utilized as the reference in selecting a better pulse soliton for optical communications.

II. NONLINEAR SCHRÖDINGER EQUATION

Basic equation governing the deployment of fiber optic pulse is a Nonlinear Schrödinger Equation which is derived from Maxwell's equations [13]. Maxwell equation is combined with the response of linear and nonlinear dielectric materials in order to obtain the general equation of soliton. NSE is more appropriate to describe the propagation of picosecond pulse in optical fiber. However for shorter pulse duration, femtosecond, NSE need a new approach to take into account other perturbation part such as the *Self perturbatif steepening (SS), Stimulated Raman Scatering (SRS),* and *Thrid Order Dispersion (TOD*) [9] [14] [15].

A. Maxwell's equations

Nonlinear effects in optical fiber observed in short pulsesas the dispersive effect can be studied by solving Maxwell's equations [16], [17].

$$\nabla \bullet D = 0 \tag{2.1}$$

$$\nabla \bullet B = 0 \tag{2.2}$$

$$\nabla x E = -\frac{1}{c}\frac{\partial B}{\partial t} \tag{2.3}$$

$$\nabla x H = \frac{\partial B}{\partial t} \tag{2.4}$$

Where *D* is electric flux density (Coulombs per square meter), *B* is magnetic flux density (tesla or webers per square meter), *E* is electric current density (ampere per square meter) and *H* is magnetic field (ampere per meter).

Maxwell equation assumes there is no charge and external electric current, then $\rho = j = 0$ [14][18], so that:

$$D = E + 4\pi P \tag{2.5}$$

$$B = H + 4\pi M \tag{2.6}$$

With *P* and *M* is the electric dipole moment per unit volume and magnetic moment per unit volume respectively. For an isotropic dielectric material which is nonmagnetic *(M=0),* so that *B = H,* and using vector identities then substitute *D* in equation (2.5) obtain [14]:

$$\nabla^2 E - \nabla(\nabla \bullet E) - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} - \frac{4\pi\partial^2 P}{c\partial t^2} = 0 \tag{2.7}$$

B. Linear Response of Dielectric Material

Material response relating the electric field *(E)* with the dipole moment of unity volume *(P).* Dipole moment per unit volume *P (r, t)* depends on the electric field at the point r, *E (r,t)* [14] [19].

In a linear dielectric theory, the relationship between the displacement field *(D)* and the electric field *(E)* from Maxwell equation is formulated as [14] [19] [20]:

$$D_\alpha(k,w) = \sum_\beta \varepsilon_{\alpha\beta}(k,w) E_\beta(k,w) \tag{2.8}$$

Where the material dielectric tensor is [13] [14]:

$$\varepsilon_{\alpha\beta}(k,w) = \delta_{\alpha\beta} + 4\pi\chi_{\alpha\beta}(k,w) \tag{2.9}$$

Equation (2.9) indicates the propagation wave with frequency *w* and wave vector *k* in a material. Dielectric tensor is depending on the frequency and the number of wave vector [13] [14].

C. Response Nonlinear of Dielectric Materials

Basic equation for wave propagation parallel to the z-axis direction is described by the electric field *E (z, t)* [14] [21]:

$$\frac{\partial^2 E}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 D}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2}{\partial t^2}P^{(NL)}(z,t) \tag{2.10}$$

With $P^{(NL)}$ is nonlinear polarization.

In isotropic medium, where the direction of polarization *P* is in the direction of the electric field *β*, the second order of susceptibility $\chi^{(2)}$ is negleted, then the response of electromagnetic waves in a nonlinear medium to the electrical medium disturbance from outside can be written as [14] [22]:

$$P_j = \varepsilon_0\left[\chi_{jk}{}^{(1)}E_k + \chi_{jkl}{}^{(2)}E_k E_l + \chi_{jklm}{}^{(3)}E_k E_l E_m + ...\right] \tag{2.11}$$

$\chi^{(n)}$ is the n-th order of electric susceptibility tensor. If the medium is homogeneous isotropic nonmagnetic and has the symmetry inversion then $\chi^{(n)}$ *=0,* so that the refractive index of the medium depends on the intencity *(Intencity Dependent of refractive Index - IDRI)* [13] [14] [22].

Refractive index equation is:

$$n = \frac{c}{n} = \sqrt{\frac{\mu\varepsilon}{\mu_0\varepsilon_0}} = \sqrt{\frac{\varepsilon}{\varepsilon_0}} \tag{2.12}$$

Power shifted can be described as [13] [14] [21] [22]:

$$\begin{aligned} D &= \varepsilon_0 E + P \\ &= \varepsilon_0(1 + \chi^{(1)} + \chi^{(2)}|E|^2 + ...) \end{aligned} \tag{2.13}$$

Where $\varepsilon = \varepsilon_0(1 + \chi^{(1)} + \chi^{(2)}|E|^2 + ...)$

And E is intensity of the refractive index of the medium, formulated as [22]:

$$n = n_0 + n_2 \tag{2.14}$$

Where :

$n_0 = \sqrt{1 + \chi^{(1)}}$ is the linear refractive index.

$n_2 \approx \chi^{(3)}$ non-linear refractive index.

D. General Solution of NSE

In a normalized form, non-linear Schrödinger equation is [13] [16] [23] [24]:

$$iE_z + DE_\alpha + \beta|E|^2 E = 0 \qquad (2.15)$$

Where E is a complex function that describes the normalized electric field and z is the propagation distance, t is the time delay, E_α is the part of temporal dispersion with coefficient $D = +1$ for anomalous dispersion region (GVD1 <0) and D = -1 for the normal dispersion area (GVD> 0). The value of β is the coefficient of *Self-Phase Modulation* [24].

Kerr effect represent the changes in refractive index of n_0 to $(n_0 + n_2|E|^2)$ so that the change is obtained as $n_2|E|^2$ [13][14][22][21]. The wave change is influenced by factor:

$$n_2|E|^2 \frac{\omega}{c} = \frac{2\pi n_2}{\lambda|E|^2} \qquad (2.16)$$

Because of the expansion of the wave numbers $(k = n\omega / c)$ around the center frequency, where the value of refractive index n is a function of ω then the decomposition of the wave modulation frequency deviates slightly from the center frequency (ω_0) [4][25], so the equation for the wave vector is:

$$k - k_0 = k^{'}(\omega - \omega_0) + \frac{k^{''}}{2}(\omega - \omega_0)^2 \qquad (2.17)$$

Based on the Kerr effect [4], the equation (2.17) becomes:

$$k - k_0 = k^{'}(\omega - \omega_0) + \frac{k^{''}}{2} g|E|^2 \qquad (2.18)$$

Then by changing the value of $(\omega - \omega_0)$ and $(k - k_0)$ with $\Delta\omega$ and Δk with $\Delta\omega \approx i\partial / \partial t$ and $\Delta k \approx i\partial / \partial z$ [4][25] the equation becomes:

$$\left(i\frac{\partial}{\partial z} + k^{'}\frac{\partial}{\partial t}\right) - \frac{k^{''}}{2}\frac{\partial^2}{\partial t^2} + g|E|^2 = 0 \qquad (2.19)$$

Equation (2.19) is operated with the electric field E (z, t) [22] [25] thus:

$$i\frac{\partial E}{\partial \xi} + \frac{k^{''}}{2}\frac{\partial^2 E}{\partial \tau^2} + g\frac{|E|^2 E}{\varepsilon^2} = 0 \qquad (2.20)$$

By replacing z and g with λ, the equation (2.20) is a general nonlinear Schrödinger equation [4] [22] [25] written as:

$$i\frac{\partial E_\omega}{\partial z} + \frac{1}{2}\sigma\mu\frac{\partial^2 E_\omega}{\partial \tau^2} + \lambda|E_\omega|^2 E_\omega = 0 \qquad (2.21)$$

If the value of $\lambda > 0$, the solution for soliton commonly known as the bright-soliton, and for the value of $\lambda < 0$, the solution is known as dark-soliton [14] [16].

III. DARK AND BRIGHT SOLITON

A. Dark Soliton

NSE can be solved by including the inverse scattering in the normal dispersion [26]. However for the positive dispersion region ($\lambda < 0$) the solution in the form of hole-soliton known as dark-soliton. In this area, the dark-soliton pulse cannot be propagated, because the solution is equal with the holes in the carrier wave of continuous light. dark-soliton will propagate in a lower rate of power and will be narrowed in a higher rate of power [17] [27].

The solution for dark-soliton is:

$$E(0,t) = A\left[1 - m^2 \sec h^2(Am\sqrt{\frac{2\delta v - \beta}{2}}(t - 2Vz))\right]^{\frac{1}{2}} \exp(i\phi) \qquad (3.1)$$

With:

$$\begin{aligned}\phi = &\tan^{-1}\left[\frac{m}{\sqrt{1-m^2}}\tanh\left(Am\sqrt{\frac{2\delta V - \beta}{2}}(t - 2Vz)\right)\right] \\ &+ A\sqrt{\frac{(1-m^2)(2\delta V - \beta)}{2}}(t - 2Vz) + V(t - Vz) \\ &+ \left[A^2\left(\frac{2\delta V - \beta}{2}\right)(m^2 - 3) - 2\delta A^3\sqrt{\frac{(1-m^2)(2\delta V - \beta)}{2}}\right]z\end{aligned} \qquad (3.2)$$

From the formulation of dark soliton above, the pulse profile can be propagated in the anomalous dispersion region.

B. Bright Soliton

Bright soliton occurs when the group velocity dispersion is in negative value [29]. The propagation of high-order pulse, femtoseconds, is shown as follows [14] [24] [28]:

$$iE_z + E_u + \beta|E|^2 + i\gamma E_{uz} = i\left[\alpha_1\left(|E|^2\right)_t E + \alpha_2\left(|E|^2 E\right)_t\right] \qquad (3.3)$$

Where z is the distance of propagation, *E* is a complex function that describes the sheath electric field, and t is the time delay. The coefficient of $(\beta,\gamma,\alpha_1,\alpha_2)$ are the *SelfPhase Modulation (SPM), Thrid Order Dispersion (TOD), Stimulated Raman Scattering (SRS),* and *Self steepening (SS)* respectively [14] [24]. For *TOD*, the value of $\gamma \propto k_{\omega\omega\omega}$ is assumed to be very small, therefore this value can be negleted [29].

By taking the value of $\alpha_1 = 3\delta$ and $\alpha_2 = -2\delta$ then [14][22][24]:

$$E = A\sec h\left[A\sqrt{\frac{\beta-2\delta V}{2}}\left(t-2Vt\right)\right]\exp \left[iVt - i\left(V^2 - \frac{A^2(\beta-2\delta V)}{2}\right)z\right] \quad (3.4)$$

The equation above is the solution of bright soliton propagating with the group velocity $(2V)^{-1}$ [14] 24].

IV. RESULT AND DISCUSSION

Numerical calculations performed using MATLAB. Pulse propagation profiles for the initial conditions described in the form of a Gaussian with, $|E(0,t)| = Ae^{-t^2}$. Figure 1 shows the profile of Gaussian pulses where the propagation of photon is consistent and concentrated towards the center.

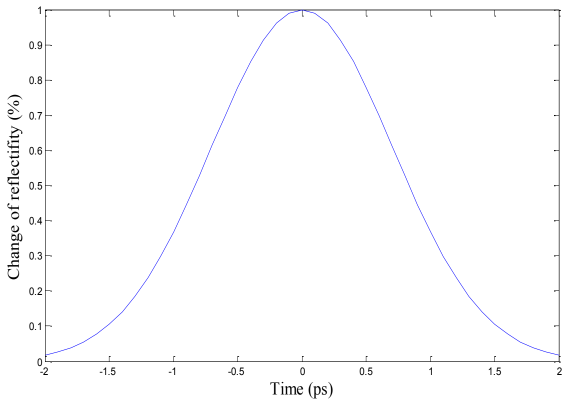

Figure 1 Gaussian pulse [12]

In bright soliton pulse width is affected by the value of *β* which describes the effect of the group velocity. Figure 2 shows that bright soliton pulse width is affected by the value of parameter *β*. The simulation is using the value of *A* = 1, δ = 0.1 and *z* = 0, and by using the value of *β* = 7 and *β* = 11, the difference in pulse width is obtained.

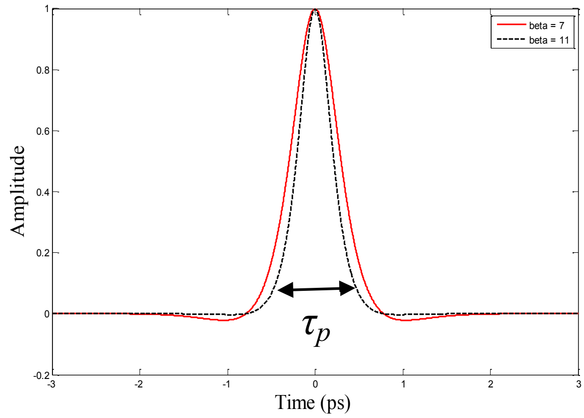

Figure 2 Bright Soliton Pulses with Different *β*

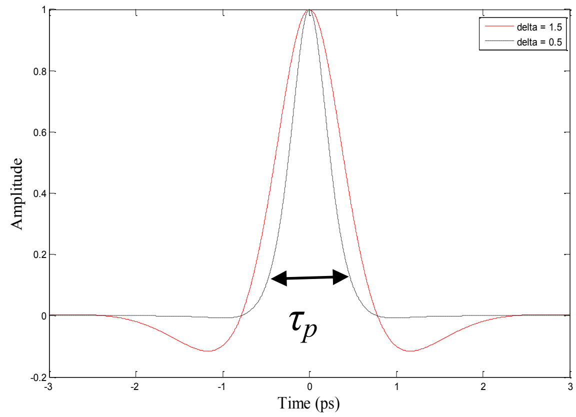

Figure 3 Bright Soliton Pulses with Different δ

Figure 2 also indicates that the changing in δ is affect to the pulse width. The higher number of δ the wider pulse width is obtained. When using δ = 0.5, the hole is formed before the peak pulse is obtained, however by using the smaller δ there is no hole in the pulse profile. The result in figure 2 and figure 3 prove that the pulse width is also affected by the group velocity.

Figure 4 shows the dark soliton profiles with the value of *A = 1, β = 11,* δ *= 2, V = 1.5, m = 0.9,* and *dt = 0.005.* dark soliton profiles is obtained as the hole, therefore it is less suitable to be applied in optical communications as a signal to carry the information.

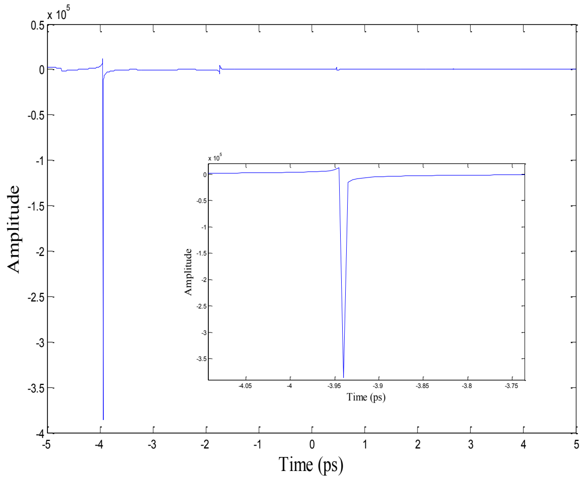

Figure 4 Profile of Dark Soliton Pulses

The simulation result in Figure 4 shows the characteristic of pulse profile for dark soliton, The profile of dark soliton is formed as a hole and it is unstable; therefore it is less suitable to be applied in optical communications.

From Figure 2 and Figure 3, the pulse profile of bright soliton has pulse width (τ_p) around 1.266 ps. However the pulse width (τ_p) of dark soliton which is shown in Figure 4 is around 0.01 ps. These simulation result shows that the soliton pulse for dark soliton tend to be very smaller than the bright soliton. Therefore bright soliton has more ability to transmit the data in optical communication.

V. CONCLUSION

Soliton is the result of the removal of nonlinear effect from a medium with the same medium dispersion effect. The wave propagation in soliton is stable so that it has capability in carry the data with large capacity and high speed, then it is appropriate to be applied in optical communication. The propagation of soliton pulses is formed as the Gaussian pulse with its propagation is concentrated to the center.

The pulse profile of bright soliton is influenced by the parameter of β and δ . This indicates that the group velocity is affecting to the pulse width of soliton. However, the characteristic of pulse in dark soliton is in the form of hole, and its pulse width tends to be narrower than in pulse of bright soliton, therefore it can be concluded that dark soliton is less suitable to be applied for optical communication.

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