Soliton Dynamics in a Birefringent Optical Fiber

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Abstract: Long-distance solitons maintain their form and speed. Single mode optical fiber exhibits birefringence as a result of its asymmetric core's effect on the refractive index. The soliton pulse is broadened and chirped as it travels through a birefringent optical fiber due to many features of the fiber. Therefore, it is necessary to strike a balance between the elements influencing the transmission to guarantee minimal data loss. This work uses OptiSysten software to strike a balance between the length, effective area, soliton period, and attenuation effects that affect the performance of the soliton while employing optical fiber as a birefringent optical fiber. Based on this research, a set of values for these parameters that minimizes widening and chirping was determined. The simulation findings are compared to the mathematical and analytical combination of soliton, which is based on the coupled non-linear Schrodinger equation. Although previous works on soliton had demonstrated the impact of GVD and SPM on the transmission, this paper aids comprehension by including additional performance-affecting characteristics.

Keywords: Birefringent, coupled nonlinear Schrodinger equation, GVD, SPM

Introduction: Current Age Telecom networks need the ability to send signals at much higher frequencies, with a much higher bit rate, and, of course, a larger capacity for storing and delivering data. These advantages of fiber optic communication over electrical copper wire connection are offset by the fact that the form of the light pulses employed in fiber optics frequently changes during transmission, leading to increased data loss. Then we have the soliton, which, thanks to a careful balancing act between nonlinear and linear influences in the medium, keeps its form and speed even after protracted transmission. The study of soliton is crucial in the field of non-linear optics. Several studies have been published in the previous few decades on this topic. The vast majority of soliton research is theoretical, and it is generally accepted that single-mode optical fiber is sufficient for soliton propagation [1]. The focus of this study is primarily the soliton in a birefringent optical fiber.

The single mode optical fiber has a constant refractive index along its two primary axes. The core of an optical fiber can become asymmetric during production. The refractive index of a single mode optical fiber with an asymmetric core is bimodal, meaning it varies along two axes. This causes noticeable variations in the pulses' group velocities. Birefringence is the dissimilarity between the group velocities along two axes. Generally speaking, birefringence renders single-mode fibers to be bimodal. However, when the pulse has components with both polarizations, the partial pulses will tend to split apart due to the presence of birefringence. While the soliton's shape and speed are preserved throughout the transmission, the soliton's dispersion might change depending on the fiber parameters. Therefore, it is important to have a thorough understanding of which parameters should be taken into account while modeling a soliton in birefringent fibers. In this study, we use a simulation approach to explore the impact of varied fiber characteristics.

In the anomalous dispersion zone, solitons are nonlinear pulses that travel without spreading out, and their behavior may be characterized by the coupled nonlinear Schrodinger (NLS) equation. In addition, analytical solutions for linked NLSE are provided.

Mathematical Analysis: Soliton works on the basis of solitary wave principle which can be described by the coupled non-linear Schrodinger equation. The coupled NLSE for soliton in birefringence fiber without any loss can be represented by following forms:

$$i\left(\frac{\partial u}{\partial \xi}+\delta\frac{\partial u}{\partial \delta}\right)+\frac{1}{2}\frac{\partial^2 u}{\partial \tau^2}+\left(|u|^2+\frac{2}{3}|v|^2\right)u=0 \qquad (1)$$

$$i\left(\frac{\partial u}{\partial \xi}-\delta\frac{\partial u}{\partial \delta}\right)+\frac{1}{2}\frac{\partial^2 v}{\partial \tau^2}+\left(|v|^2+\frac{2}{3}|u|^2\right)v=0(2)$$

Where δ is normalized group velocity, $\tau$is the normalized time.

To solve (1) and (2)following hypotheses are considered for an exact solution

$$q(x,t)=P_1(x,t)e^{i\emptyset_1} \qquad (3)$$

$$r(x,t)=P_2(x,t)e^{i\emptyset_2} \qquad (4)$$

Where $P_1(x,t)$ represents wave forms and $\emptyset_l$ represents the phase components of pulses. Thus

$$\emptyset_l=-k_l x+w_l t+\emptyset_l(5)$$

For l =1, 2 here in (5), $k_l$represents the frequency of the two solitons, $w_l$are the wave numbers and $\emptyset_l$are the phase constants.

Substituting (3) and (4) reduces (1) and (2) respectively to

$$i\frac{\partial P_l}{\partial t}-w_l p_l+\frac{1}{2}\left(\frac{\partial^2 P_l}{\partial x^2}-2ik_l\frac{\partial P_l}{\partial x}-{k_l}^2 P_l\right)+{P_l}^3+\frac{2}{3}P_l{P_{\bar{l}}}^2+i\delta_l\frac{\partial P_l}{\partial x}+\delta_l k_l P_l=0 \qquad (6)$$

For *l* =1, 2 and $\bar{l}$= 3−*l*. Now, the real and imaginary parts of the equation (6), respectively are

$$-\left(w_l+\delta_l k_l+\frac{1}{2}{k_l}^2\right)P_l+{P_l}^3+\frac{2}{3}P_l{P_{\bar{l}}}^2+\frac{1}{2}\frac{\partial^2 P_l}{\partial x^2}=0 \qquad (7)$$

$$\frac{\partial P_l}{\partial t}-k_l\frac{\partial P_l}{\partial x}+\delta_l\frac{\partial P_l}{\partial x}=0 \qquad (8)$$

For bright solitons,

$$P(x,t)=A_l sech^{p_l}\tau e^{i\emptyset_l}(9)$$

For l=1, 2 where $A_l$represents the amplitude of the soliton. Also,

$$\tau=B(x-vt)(10)$$

Where*B* is the two pulse's width and *v* indicates the velocity with which the two polarized pulses travel.

Now, the real part of the equation (6) which is given by (7) reduces to

$$\left\{-\left(w_l+\delta_l k_l+\frac{1}{2}{k_l}^2\right)A_l+{P_l}^2A_lB^2\right\}sech^{p_l}\tau-\frac{1}{2}P_l(2P_l+1)A_lB^2sech^{P_l+2}+\frac{2}{3}A_l{A_{\bar{l}}}^2sech^{P_l+2P_{\bar{l}}}$$
$$+{A_l}^3sech^{3p_l}\tau=0 \qquad (11)$$

While the imaginary part of the equation (6) given by (8) reduces to,

$$(-\nu P_l - \delta_l P_l + k_l P_l) sech^{P_l} \tanh \tau \, A_l B = 0 \qquad (12)$$

This is the desired solutions of coupled NLSE for soliton in birefringent optical fiber.

Simulation and Results: Experimental setup is shown in Fig-1 for transmitting information up to 1000km using soliton parameters in birefringent optical fibers.

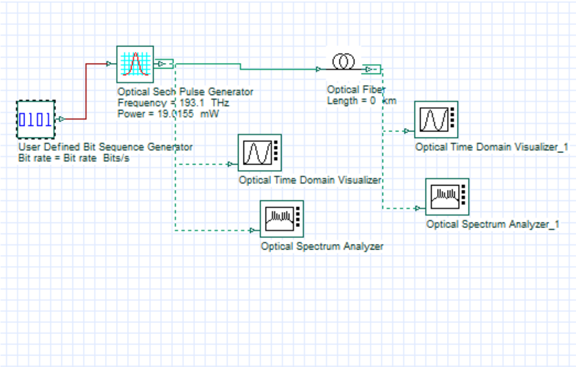

Fig 1: System Layout

Fig 1 shows the layout for fundamental soliton N=1.The simulation is done in OptiSystem software. For given $n_2 = 3e - 020\ m^2/W, A_{eff} = 93\ um^2,\ \lambda = 1550nm$ and $\beta_2 = -20\ ps^2/km$. The fiber length is set to 631.72km. Initial pulse has a sech shape. Pulse power for fundamental soliton is 19.0155 mW.

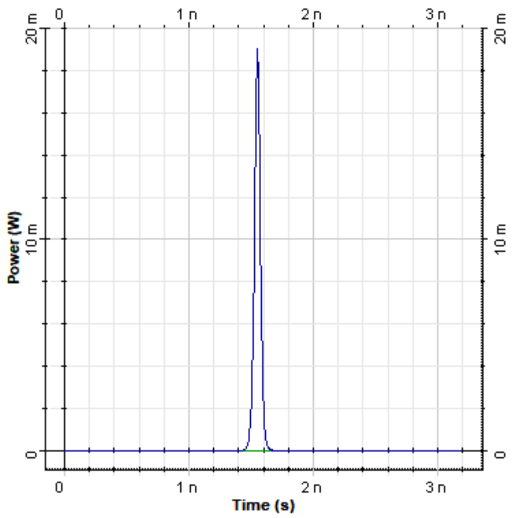

Fig 2: Input Signal

After traveling 631.72 kilometers through a lossless fiber, the input pulses are displayed in Figure 2. Due to GVD, there is now a 1 millisecond delay between the two partial pulses' arrival times, which is the same as if the fiber was 1 kilometer longer. The birefringence is responsible for this change.

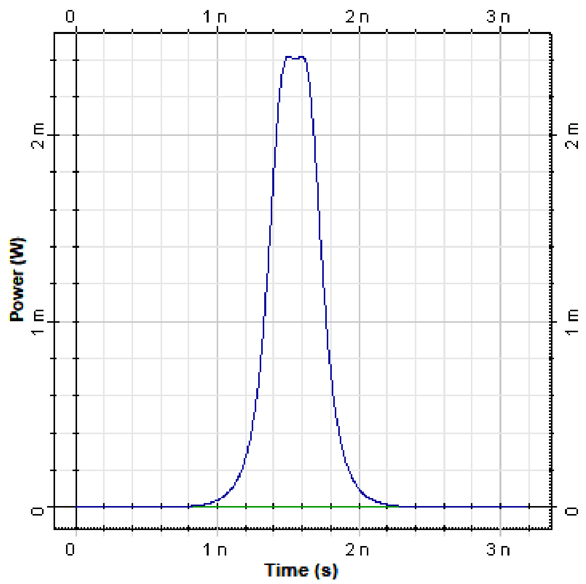

Fig. 3: Output Signal

Although in theory a soliton should experience no dispersion, in practice soliton does. However, the behavior of the soliton changes with the values of the parameters, and this may be seen in the accompanying graphs, where the values of the parameters are displayed along the x axis, and the ratio of the corresponding parameter to the width of the output pulse is shown along the y axis. In this research, we focus on studying the effects of different kinds of external potentials on soliton solutions that could be used in optical communication systems. Our findings also suggest that new soliton control approaches based on fiber characteristics and external potential could be created. Potentially useful in soliton communication systems, this could also improve the realism of the soliton control method.

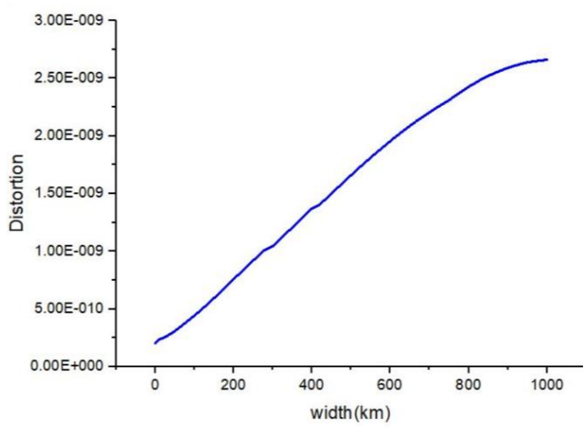

Fig. 3: Distortion vs. Width for varying fiber length

Figure 3 demonstrates that the distortion grows sharply from 0 to 300 km, then levels out, and finally declines as the fiber length reaches 1000 km, indicating that transmission lines longer than 1000 km display anomalous behavior.

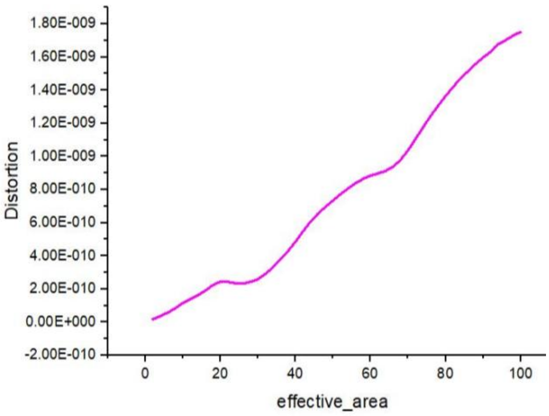

Fig. 4: Distortion vs. effective area

For a fiber with a length of 631.72 kilometers, here is another relationship between the effective area and the distortion. As the effective area shifts, the distortion in this example grows.

Conclusion: Since the soliton pulse retains its waveform over extended distances, it has the ability to achieve a sophisticated optical transmission system, making it one of many optical transmission formats with significant potential. A perfect soliton requires a constant dispersion lossless fiber. However, the quality of the soliton pulse is drastically reduced in a real system due to loss and changing dispersion. While the soliton's shape and speed are preserved throughout the transmission, the soliton's dispersion might change depending on the fiber parameters. Therefore, it is important to have a thorough understanding of which parameters should be taken into account while modeling a soliton in birefringent fibers. OptiSystem software was used to extract various pieces of information from the fiber model for this purpose. The characteristics can be seen by measuring the broadening at the output terminal for the identical input pulse at different fiber lengths and then plotting this broadening against the relevant parameter.

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