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Soliton Light Wave Propagation in Fiber Bragg Grating

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ABSTRACT

Soliton is a type of light wave that can maintain its shape and speed during travel, albeit through a varied medium. Fiber Bragg Grating (FBG), on the other hand, is a structure in optical fibers with a periodic refractive index, serving as a selective filter or mirror that reflects certain wavelengths while allowing others to pass through. The combination of soliton and FBG offers great potential in improving modern optical communication systems. FBG plays an important role in controlling and stabilizing the propagation of soliton waves. With its ability to eliminate dispersion, FBG helps the soliton maintain its shape, which is essential for maintaining signal integrity during long-distance transmission. Dispersion is a phenomenon that causes the spread of light signals in optical fibers, which can result in a decrease in signal quality and data transmission speed. With FBG, this dispersion effect can be minimized, ensuring that the soliton remains unchanged throughout its journey. In the context of optical communication technology, FBG enables faster and more reliable data transmission, which is essential to meet the demand for high-speed, large-capacity communication networks. In addition, FBG can be used in laser technology and other optical devices to improve performance and efficiency.

Keywords: *Waves, Dispersion, Soliton, FBG*

1. Introduction

a. Soliton

A solitaire or solitary wave is a physical phenomenon in which waves propagate without changing shape in a dispersive medium. The soliton was first discovered by John Scott Russell in 1884 when he observed *Shallow water*. The soliton phenomenon occurs due to the balance between the dispersion and nonlinearity effects (Yuliawati et al ., 2019).

If two solitions are placed apart and each creeps closer to each other at a constant shape and speed, then as the two waves get closer and collide, gradually change shape then into a single wave package. The soliton wave, so called because it often occurs as a single, localized entity, was first observed by J. Scott Russell on the Edinburgh-Glasgow canal in 1834; He called it the "Great Wave of Translation" (Sholikah , 2019) .

The development of soliton pulses is one of the focuses developed in optical technology. A Japanese scientist named Akira Hasegawa in 1973 first showed that soliton could be used in optical fiber communication. Robin Bullough continued mathematically and proposed a soliton-based transmission system on optical fibers (Fadhian , 2015) .

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Soliton as a nonlinear wave has relatively different properties from waves in general. Soliton waves have several unique characteristics, including: (Deng et al., 2019; Lu et al., 2019; Manahan et al., 2019)

1. Shape Stability

   Soliton has the ability to maintain its shape and speed even if it is disturbed or encounters other soliton. This phenomenon is known as soliton robustness. The stability of this soliton form results from the balance between the nonlinear and dispersion effects contained in the equation that provides the soliton solution.

2. Non-Dispersion Propagation

   Soliton is able to travel long distances without experiencing deformation or wave dispersion. This happens because there is a perfect balance between the nonlinear effect, which causes the waves to focus, and the dispersion effect, which tends to propagate the waves. The interaction between these two effects creates conditions in which soliton waves remain stable and do not deform during their propagation.

3. Overlap and Soliton Interactions

   Soliton can interact or overlap with other soliton without losing their identity or true nature. After the interaction, the soliton will return to its original shape and velocity. The nature of these interactions between solitones is elastic, similar to how particles collide.

4. Particle-Like Behavior

   Soliton exhibits similar behavior to particles in various aspects, including in impact, refraction, and reflection. Just like particles, soliton can undergo elastic impact, bounce when it hits a barrier, and undergo refraction when traversing different mediums.

5. Applications in Nonlinear Systems

   Soliton is a critical solution in nonlinear systems including nonlinear optics, quantum mechanics, plasma physics, and fluid dynamics. The unique characteristics of the soliton make it an invaluable tool in various research areas.

6. Soliton in the Dissipation System

   Soliton can also be found in dissipative systems, where there is an energy loss or attenuation. In this context, the characteristics of the soliton differ from those in conservative systems; For example, there is a gradual shift in frequency and shape.

To form a soliton on the solution of the wave equation, the solution will be equivalent to the soliton profile. Based on the reduced wave equation of the spatial one-dimensional case of the x direction, the wave equation can be written as,

$$\psi(x,t) = Bcos(x \pm t)$$

If the equation is written in the cosine series as follows,

$$\psi(x,t) = B\{1 - \frac{\xi^2}{2!} + \frac{\xi^4}{4!} - \cdots\}$$

where. If the equation is equivalent to the soliton profile (, then the expression C is$\xi = x \pm t \psi(x,t) = C\{\{1 + \frac{\xi^2}{2!} + \frac{\xi^4}{4!} + \cdots\})$

$$C = B\{1 - \frac{\xi^2}{2!} + \frac{\xi^4}{4!} - \cdots\}\{1 + \frac{\xi^2}{2!} + \frac{\xi^4}{4!} + \cdots\}$$

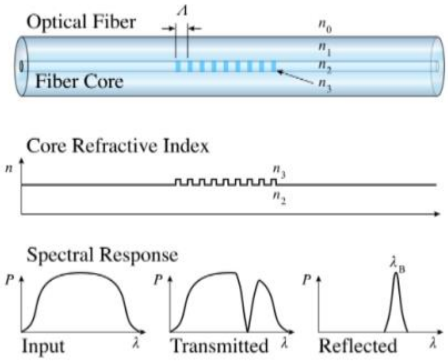
So based on the result of the equivalence, the wave equation can be written as

$$\psi(x,t) = C(x \pm t)D(x \pm t) \text{ or } \psi(x,t) = C(\xi)D(\xi)$$

b. Fiber Bragg Grating (FBG)

Fiber Bragg Grating (FBG) is a fiber optic technology that has a lattice arrangement at the core with periodic modulation on its refractive index (Hill & Meltz , 1997; Zailani , 2016) .

FBG is made of single-mode fiber optical fibers that are made in a pattern using a laser beam interference technique that produces a refractive index that changes periodically at the core. Thus, light waves passing through optical fibers will experience an attenuation in intensity at Bragg wavelengths. (James & Birch, 2013; Lo Presti et al ., 2020; Mahdi Hammadi, 2020)(λ_B)



Picture 1. FBG structure with refractive profile index and spectral reponons

When light passes through FBG, part of the light will be reflected at a certain wavelength value or commonly called Bragg wavelength, and part of it is transmitted. The Bragg wavelength, depends on the lattice period and the guiding properties of the FBG, i.e. the effective refractive index. The effective refractive index is the ratio of the speed of light propagation to its speed in a vacuum, the value of which depends not only on the wavelength, but also on the mode in which the light travels.(λ_B) (Patra & Lenses Barpanda , 2016) $(\lambda_B)(n_{eff})(n_{eff})$ (Setiono dkk., 2016)

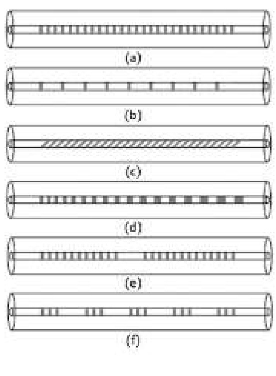


Figure 2. Types of FBG Based on the Structure of the Grid:
(a) Uniform (b) Long Period (c) Tilted (d) Chirped (e) Phase Shifted (f) Superstructure (Nur Guidance , 2022)

2. Writing Methodology

This study uses a qualitative methodology approach. Data and information are obtained through a literature review process from various *sources up to date* and relevant. The data and information are then presented in this study in a narrative manner. We used the literature analysis method by using the keywords "soliton waves, fiber bragg grating". Literature studies are conducted by reviewing existing research journals and then evaluating. Findings and analyses are obtained through the collection of information from various sources, including journal reviews.

3. Discussion

a. Soliton in Fiber Bragg Grating

In an investigation by Chen and Mills in 1987, they found a strong localization of monochromatic electric fields within structures with frequencies right inside the FBG. They call this remarkable object a "soliton gap" that is a light-shaped soliton profile. This marked the beginning of the study of soliton in the periodic optics of the system.

Soliton is a nonlinear wave or wave pulse consisting of many components. In the development of soliton in FBG there is an imbalance that has managed to bring a wide range of applications and devices in fiber optics in the field of communication. Nonlinear Bragg that has low reflectivity can make it possible to get waves with very low layer intensity.

In general, an optical pulse that is proportional to the optical fiber will undergo a deformation. The change in shape that occurs is biased widened due to dispersion or other shape changes. The movement of soliton pulses can be said to be limited because it has a non-dispersed nature. Soliton can also exist outside the band gap. In contrast to the gap soliton which is in the form of a bright soliton, they found that (Fadhian et al ., 2015)*the out-gap soliton* consists of an anti-dark soliton, that is, a light soliton on a base, and a dark soliton. The existence of this moving solitonic pulse occurs as a result of the subtle interaction between the linear lattice coupling leading to the induction of the dispersion lattice, and the nonlinear term responsible for the self-focusing effect.

The soliton gap is obtained when the spectrum of the solyton of the bragg lattice is located within the photonic band gap. From the experiment it was stated that soliton could be generated by input pulses, many physical systems were described as inintegrable systems that had a stationary or mobile local solution. These collisions between solitary waves are usually inelastic, which is a clear indication that they are not elastic for true solitons. When photons are trapped in a soliton, the soliton collision can be used to implement some operations that may prove useful in quantum communication and computing

Optical slit soliton refers to nonlinear waves that propagate in optical fibers whose linear refractive index has periodic variations. The soliton gap can be obtained when the spectrum of the solyton of the bragg lattice is located within the gap of the photonic band. In effective communication, the propagation of light unaffected by the waveguide until the end of the transmission becomes the most important criterion. These waves have a behavior called soliton. Waves propagate without experiencing any change in their properties.

In fiber optic communication, Soliton pulses are proposed as bit carrier information. Fiber optic communication using Soliton pulses as optical *carriers* can transmit data with a large capacity and without the use of repeaters. Soliton pulses are used in long-haul communications because they can overcome limitations caused by *internal losses*.

In optical fibers, the soliton waves that occur are in the form of soliton packets that function to carry information consisting of several channels at once without changing the intensity. This can happen because it is caused by the nonlinear effect of Kerr and the dispersive effect that occurs in the medium. Bragg Mesh Fibers can be used as input optical filters to block out specific wavelengths, or as specific wave reflectors. Most bragg lattice fibers are used in single-mode fibers, which in physical modeling are often relatively simple. (Siahaan et al ., 2015)

b. Soliton Wave Conductivity

These soliton have a balance between nonlinear and dispersion effects referred to as temporal solitones (Zaera et al ., 2018) . In addition, in nonlinear plasma systems, the equations used to visualize solitons are Partial Differential Equations (PDEs), the same as those first performed by Washimi and Taniuti who used the Korteweg-deVries equation (KdV) for acoustic ion solitons. . (El- Tantawy dkk., 2011)

The KdV equation consists of three terms, namely non-linear terms, dissipative terms, and terms that contain derivatives of time t. In general, the KdV equation is shaped;

$$u_t + auu_x + su_{xxx} = 0$$

with *auux* as a nonlinear term and *suxxx* as a dispersive term. The analytical solution of the KdV equation is,

$$u(x,t) = \frac{2sk^2}{\alpha}\operatorname{sech}^2(k(x-4sk^2t))$$

for a *k* and *x0*. This solution draws a soliton that is dormant all the time t. From the solution, dispersive coefficient exerts an effect on the height and speed of soliton propagation, which is *s* directly proportional to the height and speed of soliton propagation. (Ahmad, 2016)

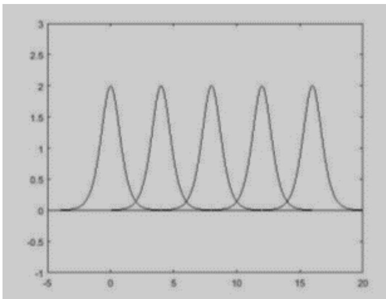


Figure 3. Exact Solution of the KdV Equation at Time t = 1 s,t = 2s,t = 3s,t = 4s, and t = 5s for α = 1 and s = 1.

One interesting example of nonlinearity in soliton waves is the phenomenon of soliton collisions. In this phenomenon, there is a nonlinear interaction between two solotons, both large solitones chasing small solitones (*overtaking solitons*), and collisions of soliton facing each other (*head on collision*). This nonlinear phenomenon can cause large wave amplification. When there is a collision of two solotons, for example a soliton with an amplitude and then the maximum wave height of these two waves meeting (superposition) can be written as a_1a_2

$$M = a_1 + a_2$$

where *M* is the amplification factor. The theory of the linear approach provides, however, for nonlinear cases with a specific angle of entry, it may be found. In research on tsunamis, these soliton collisions were used to study the amplification of nonlinear waves in the design of sea embankments. $.m = 1m = 2$ (Yuliawati et al ., 2016)

4. Conclusion

Soliton is a wave of light that retains its shape during travel, and FBG is a structure in optical fiber that has a periodic refractive index to filter out specific wavelengths. Then FBG can control and stabilize the propagation of soliton waves, which is beneficial in optical communication systems. With FBG, the dispersion that normally affects the soliton can be minimized, maintaining the integrity of the signal throughout the transmission. Therefore, the integration of soliton waves with FBG can improve the performance and reliability of optical communication systems, enabling more efficient and fast data transmission. The nonlinear Kerr effect neutralizes the dispersion effect that occurs when the propagation does not widen in time until the detector causes the soliton to occur. The potential value of the wave in FBG increases, the amplitude value also increases, and vice versa, if the potential value of the wave is small, the amplitude value is also getting smaller.

5. Pronunciation

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