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Investigation of Transmission and Reflection of Single Mode Fiber Bragg Grating

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Abstract: The use of Single Mode Fiber Bragg Grating (SMFBG) has been increasing in recent years due to its compact size, low cost, fast response and immunity to electromagnetic interference. It is commonly integrated into medical devices for long-distance light transmission and collection due to its high flexibility, low propagation loss, compatibility and tolerance to electromagnetic interference. SMFBG is a device made of thin glass material that is used as a medium for transmitting information in the form of light signals sourced from lasers or LEDs from one location to another. It consists of 3 main components, namely core with a certain grating, blanket (cladding) and jacket (coating). The advantage of optical fiber is that the data when transmitted is converted into light so as to reduce the risk of data damage. Other advantages include very small size, minimal interference with electromagnetic waves, resistance to temperature changes, attenuation when the transmission process is small enough, and large enough bandwidth. The orientation of this literature review is to understand the concept of optical fiber, the concept of reflection and refraction, and how light propagates in optical fiber.

Keywords: Fiber optic; Reflection; Refraction; Single mode

Introduction

Much progress has been made in recent years in the use of fiber optics (Ballato et al., 2021), from food safety, environmental monitoring, drug development, clinical diagnosis and biological research to improve testing systems that are fast, reliable and highly sensitive. Due to its compact size, very small size, low cost, fast response and immunity to electromagnetic interference, optical fiber is an excellent choice to meet the requirements (Hoseinian et al., 2019), and is also widely used in the field of physics and chemistry (Fleming et al., 2018). According to Losh Optical fiber is commonly integrated into medical devices for long-distance light transmission and collection due to its high flexibility, low propagation loss, compatibility and tolerance to electromagnetic interference (Losch et al., 2022).

Light propagation is synonymous with the depiction of the concepts of reflection and habituation because it makes it easier to describe refractive and reflected rays when they hit the boundary plane of an optical object (Hamdani et al., 2018). The concepts of reflection and habituation are described by Snellius' Law. The factor affecting reflection and habituation is the medium through which light rays pass. Mediums have different refractive indices depending on the type of medium. The refractive index is a parameter to see the ability of a medium to propagate light rays. Reflection occurs when a ray travels through two similar mediums with the same propagation speed, while habituation occurs when a ray passes through the boundary plane of two different mediums with different propagation speeds (Irawan et al., 2010). The concept of reflection and habituation was then developed by scientists and created Optical Fiber which is used as a medium of

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information transmission to this day (Löffler-Mang, 2012).

Optical Fiber is a cable made of thin glass material that is used as a medium for transmitting information in the form of light signals sourced from lasers or LEDs from one location to another (Yugay et al., 2022). Fiber optic cable has a diameter of approximately 120 micrometers. Optical Fiber consists of 3 main components, namely core, blanket (cladding) and jacket (coating) (Efriyanda et al., 2018). The advantage of optical fiber is that the data when transmitted is converted into light so as to reduce the risk of data damage. Furthermore, the data transmission process becomes more accurate, fast and relatively stable to changes in the environment when compared to conventional cables (Saktioto et al., 2021). Other advantages are very small size, minimal interference with electromagnetic waves, resistance to temperature changes, attenuation when the transmission process is small enough, and large enough bandwidth (Fon et al., 2023). The characteristics of optical fiber forming materials greatly affect the transmission of rays (Silveira et al., 2020).

The orientation of this literature review is to understand the concept of optical fiber, the concept of reflection and refraction and also be able to know how light propagates in optical fiber.

Literature Review

Optical Fiber (Waveguide)

Optical fiber is a waveguide or optical wave transmission medium made of very small glass or plastic (Li et al., 2021). Optical fiber generally consists of 3 components. An optical fiber consists of several essential components that enable its function in transmitting light signals over long distances. At its core, the optical fiber features the most crucial component known simply as the core. This core serves as the medium through which the optical waves travel, distinguished by its higher refractive index compared to the cladding layer. Typically made of glass, the core varies in diameter depending on the type of optical fiber being used.

Surrounding the core is the cladding layer, forming the second vital component of the optical fiber. The cladding, made of material with a lower refractive index than the core, facilitates the reflection of light back into the core, allowing it to remain trapped within the fiber and minimizing signal loss during transmission.

Lastly, the optical fiber is encased in a protective layer known as the jacket. Composed of elastic plastic materials, the jacket shields the optical fiber from physical damage and external interference, ensuring the integrity and longevity of its transmission capabilities (Sabana, 2021). Together, these components form a cohesive structure that enables efficient and reliable transmission of optical signals across various telecommunications and networking applications.

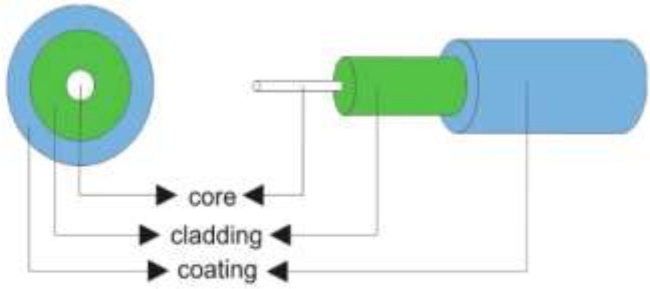

Figure 1. Fiber optic structure

Reflection and Refraction

Optical waves that propagate from one medium to another will experience reflection and refraction events. Light reflection occurs when a beam of light approaches the boundary between two different media so tightly that the light beam radiates in opposite directions and is in one medium (Pedrotti et al., 2017).

Total Internal Reflection

In refraction, it can be seen that the angle of light propagation will increase if light enters a medium that has a smaller refractive index. When the angle of incidence of light rays (in the first medium) against the boundary plane continues to be magnified, there will be an event where the angle of refraction becomes 90° so that light will propagate parallel to the boundary plane in the second medium (Irawan et al., 2022). The angle of incidence will cause a critical angle. In optical fibers, light is transmitted in the form of rays. In order for light to be reflected entirely, an angle of incidence is required that must be greater than the critical angle for continuous reflection to occur on the wall cladding. This reflection event is called Total Internal Reflection (Zanoon, 2014).

Numerical Aperture

The effectiveness of light propagation in optical fibers is influenced by the ability of optical fibers to guide light over long distances with little scattering or absorption of light (Rashed et al., 2022). This can be done by arranging for total internal reflection events to occur in optical fibers. The parameters that need to be considered for total internal reflection in optical fiber are the Numerical Aperture (AN) value and the refractive index profile of the type of optical fiber used (Campanella et al., 2018; Rahmatulloh et al., 2023).

Method

In this paper we use the method of literature study or conduct a review of various books and other scientific works (Gurendrawati et al., 2023), which is related to the topic raised, namely Reflection and Refraction in Optical Fiber. This study aims to find out the concept of optical fiber, the concept of reflection and refraction and propagation of light on optical fiber, so that it can benefit the community.

Result and Discussion

Reflection and Refraction

When a beam of light passes through a medium that has a different refractive index from each other, there will be a process of refraction or reflection which can be explained using Snellius' Law as follows according to Luetjen et al. (2013) and Hasbun (2018): The refractive index of a medium is the value of the rapid comparison of the propagation of light in a vacuum with the rapid propagation of light in the medium (Khan et al., 2022). When the incident beam penetrates the boundary plane between the two mediums with different refractive indices as illustrated in Figure 2(a), the rays moving close to the boundary plane will be propagated in the medium with the refractive index i.e. n1 which forms an angle Φ1 with respect to the normal line of the surface of the medium. For the medium on the other side of the boundary plane with a refractive index that is n2 smaller than n1, the refractive angle will form an angle Φ2 to the normal line, where Φ2 is greater than Φ1. The relationship between the incidence angle Φ1, the refractive angle Φ2 and the refractive index of the medium can be expressed in Snell's law of refraction.

$$\frac{sinsin\,\Phi_1}{sinsin\,\Phi_2} = \frac{n_2}{n_1} \tag{1}$$

From Equation (1) the value of the critical angle is given by;

$$Sin\ \Phi c \frac{n_2}{n_1} \tag{2}$$

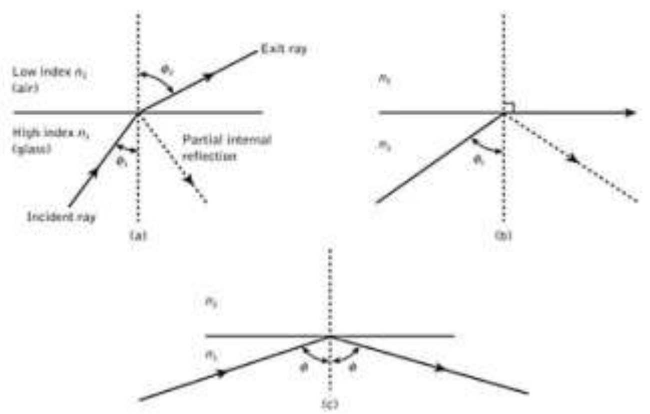

Figure 2. (a) The process of reflection and refraction of rays, (b) Critical angle (c) Total internal reflection (Mulkerns et al., 2022)

Figure 2(b) shows the formation of a critical angle that occurs when the refractive ray is parallel to the boundary plane of the medium, so the angle Φ1 is called the critical angle. Figure 2(c) is called total internal reflection, when the angle of the incident beam is magnified continuously so that it exceeds the critical angle Φ1 > Φc, the incident ray will be reflected entirely. This concept of total internal reflection is used as the basis for optical waveguides intended to transmit light ray waves through optical mediums such as optical fibers (Eid, 2022).

Reflection and Refraction in Single-Mode Fiber

Single-Mode Fiber is a single-stranded glass fiber that allows only one beam of light signals to be propagated. The core diameter of single-mode optical fiber is 8 μm. Single-Mode fiber is more expensive and is commonly used to reduce distortion (Winzer et al., 2018).

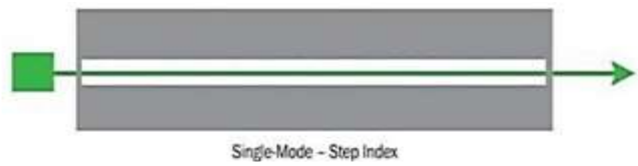

Figure 3. Single-mode fiber

Reflection and Refraction in Multi-Mode Fiber

Multi-Mode Fiber is a type of fiber designed to carry many rays or modes of light simultaneously, each at a slightly different reflection angle within the optical fiber core. Multi-mode cables consist of glass fibers with a common diameter ranging from 50 to 100 μm for light-carrying elements (Zhao et al., 2022). Based on changes in the refractive index of the material, multi-mode fibers are classified into two, namely step-index fiber and graded-index fiber (Elsherif et al., 2019) .

Step-Index Multi Mode

In this type, the refractive index in the cores is uniform. This multimode step-index fiber works on the principle of perfect reflection that allows light transmission across the fiber's cores in a zigzag pattern (Salih, 2021).

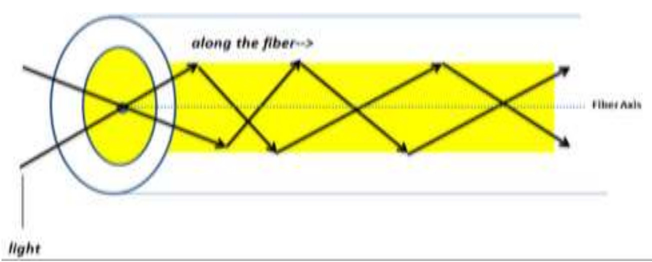

Figure 4. Step-index multi mode

Light entering this type of fiber has different angles of incidence so that it passes through different paths for effective operation. Each beam of light propagates at the same speed as it travels across the core of the optical fiber, but the time it takes to exit the optical fiber depends on the angle of incidence (Irawan et al., 2011). Light rays that enter at a steeper angle will have more reflection so that light that comes out more slowly than light beams that enter at a less steep angle (Monir et al., 2023).

Graded-Index Multi Mode

Graded index fibers have an inhomogeneous core refractive index. A higher refractive index is found on the core axis line and the refractive index decreases gradually as the distance from the core axis increases (Nsengiyumva et al., 2022).

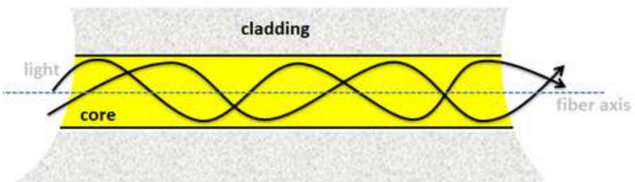

Figure 5. Graded-index multi mode

This gradual change in the refractive index results in internal refraction. Thus the light beam is deflected towards the axis of the fiber as it moves through the fiber with a low refractive index (Azhar et al., 2021). In this type of fiber there is almost no complete reflection because the light beam is forced back to the core axis before hitting the cladding (Tian et al., 2023).

Numerical Apparatus

Numerical aperture is a parameter whose value is determined by the refractive index of the core (core) and blanket (cladding). Together with core size and wavelength, numerical aperture determines the number of modes of light received at the core of an optical fiber.

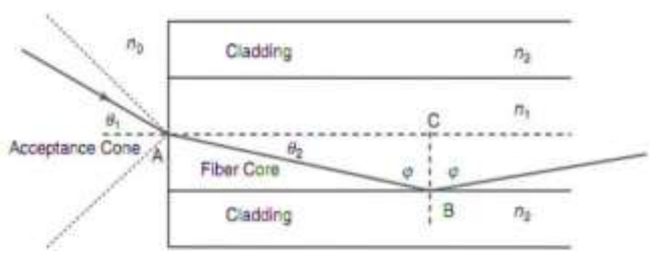

Figure 6. Geometry for lowering the acceptance angle (Khudyakov et al., 2022)

Figure 6 illustrates the geometry of decreasing the angle of reception (θacc). To qualify for total internal reflection, the beam arriving at the interface between the fiber and the outer medium, e.g. air, must have an angle of incidence less than θacc, otherwise the inner angle will not meet the total reflection requirement, and the energy of the beam will be lost in cladding.

Suppose a ray with an angle of incidence is less than θaccSay θ1, enters the fiber at the interface of the core (n1) and the outside medium, say air (n0), and the beam lies in the meridional plane. From Snell's Law we derive (Zhang et al., 2023).

$$n0\ Sin\ \theta 1 \ = \ n1\ Sin\ \theta 2 \tag{3}$$

From a right triangle ABC (Figure 6), the angle Φ is given by Equation 4.

$$\Phi = \frac{\pi}{2} - \theta_2 \tag{4}$$

If the angle Φ is greater than the critical angle, then substituting equation 4 into equation 3 is obtained:

$$n0\ Sin\ \theta 1 \ = \ n1\ Cos\ \Phi \tag{5}$$

When the incident angle (θ1) approaches θacc and the inner angle approaches the critical angle Φcrit of total reflection. Using the trigonometric relationship sin2Φ + cos 2Φ = 1, then substituted to equation 7, it is obtained:

$$\begin{aligned} n0\ Sin\ \theta 1 \ &= \ n1\ Cos\ \Phi \\ &= \ n1\ (1 \ - \ sin2\Phi)^{\frac{1}{2}} \\ &= \ n1\ \left(1 - \frac{n_2}{n_1} 2\right)^{\frac{1}{2}} \\ &= \ (n12 \ - \ N22)^{\frac{1}{2}} \end{aligned} \tag{6}$$

This equation defines the angle at which the fibers can receive and scatter light and is referred to as the "Numerical Aperture" (AN).

$$AN \ = \ n0\ Sin\ \theta acc \ = \ (n12 \ - \ N22)^{\frac{1}{2}} \tag{7}$$

If the medium with a refractive index of n0 is air, the equation AN for glass fibers is simplified to:

$$AN \ = \ sin\ \theta acc \ = \ (n12 \ - \ N22)^{\frac{1}{2}} \tag{8}$$

This equation states that for all incidence angles that satisfy the inequality 0 ≤ θ1 ≤ θacc, then the incident rays will propagate on the fibers. The AN parameter expresses the tendency of the fiber to receive and scatter light in a dense cone determined by an angle of 2θacc. The AN equation can also be expressed in terms of the difference between the refractive index of the nucleus and the cladding, i.e. (Ansari et al., 2023).

$$\Delta = \frac{{n_1}^2 - {n_2}^2}{2{n_1}^2} \approx \frac{n_1 - n_2}{n_1} \tag{9}$$

With this simplification, AN can now be written as follows Equation 10 (Singal, 2016).

$$AN = n1(2\Delta)^{\frac{1}{2}} \tag{10}$$

Since numerical aperture relates to the maximum angle of incidence (i.e., angle of acceptance), equation (10) is used as a measure of the fiber's ability to receive light to be guided. The transmission, reflection and refraction in SMFBG is significantly affected by a grating. The grating causes the input signal will be reflected to the contrast direction.

In this paper we propose a FBG sensor design layered with single layer graphene material and polymeric materials such as Chromium Oxide, PMMA, Aluminum, and TOPAS and it will be investigated in a temperature range of 25°C – 300°C, in addition, apodization and chirping profiles are also used in FBGs for sensing accuracy enhancement.

The distribution of refractive indexes throughout FBG can be written with the equation 11 $n_{eff}(z)$

$$n_{eff}(z) = n_0 + f(z)\Delta n_{ac} v\cos\left(\left(\frac{2\pi}{\Lambda}\right) + \theta(z)\right) \tag{11}$$

Where z is the positionn_0, FBG's initial refractive index, Λ grating period,Δn_{ac}modulation refractive index amplitude, f(z)apodization function, is the chirp function where C is the chirp parameter, v fringe visibility. $\theta(z) = 2\pi Cz^2/\Lambda$

Here are some types of profile apodization and its functions:

Uniform

$$A(x) = 1, \text{ where } 0 \leq x \leq L \tag{12}$$

Gaussian Function

$$A(x) = exp\left(-\ln 2\left(\frac{2\left(x-\frac{L}{2}\right)}{0.5L}\right)^2\right) \tag{13}$$

where $0 \leq x \leq L$

Tanh Function

$$\mathrm{A(x)} = \tanh\left(4\frac{\mathrm{x}}{\mathrm{L}}\right)\tanh\left(\frac{1\text{-x}}{\mathrm{L}}\right) \tag{14}$$

where $0 \leq x \leq L$

Meanwhile, the normal temperature sensitivity of an FBG is given as follow on Equation 15.

$$\frac{\Delta\lambda_{Bragg}}{\lambda_{Bragg}} = \Delta T[\varphi + \vartheta] \tag{15}$$

It can be seen clearly from the Equation 7 that Bragg wavelength φ is significantly affected by the thermal expansion of the coating material on SMFFBG as function of temperature changeΔT, φ is the coefficient of thermal expansion and ϑ the thermo-optic coefficient. The Silica material has thermal expansion coefficients (φ) and thermo optic coefficients (ϑ) of $0.55 \times 10^{-6}/^{o}C$ and $8.3 \times 10^{-6}/^{o}C$respectively. The

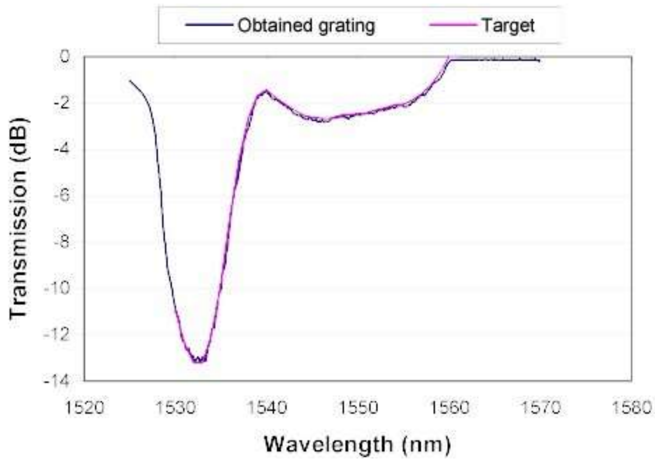

Figure 7. Transmission profile of SMFBG

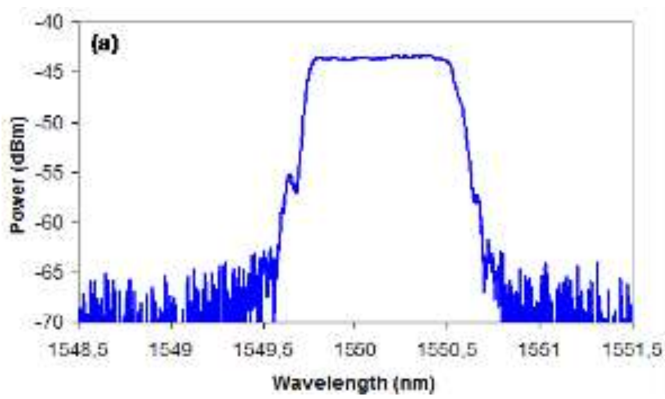

Figure 8. Reflection profile of SMF FBG

Transmission profile of the SMF FBG is given by Figure 7. It can be seen clearly that the transmission profile has the narrowest peak at 1537 nm. Figure 8 shows the transmission profile of SMF FBG. It can be seen clearly that the transmission profile has wider bandwidth around the input wavelength of 1550 nm.

Conclusion

Optical fiber is a data transmission medium that utilizes the concepts of reflection and refraction to transmit data in the form of light ray waves. The advantage of optical fiber is that the data when transmitted is converted into light so as to reduce the risk of data damage. Other advantages include very small size, minimal interference with electromagnetic waves, resistance to temperature changes, attenuation when the transmission process is small enough, and large enough bandwidth.

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Author Contributions
Literature review, D. I, A, S; Method, D.H, B.W; Investigation, D. I, A, S, D. H, B. W; Analysis, D. I, A, S, D. H, B. W.

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Conflicts of interest
There is no conflicts of interest in this article.

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