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Interference of Light Waves in Optical Fiber

Clariza Aprilia[1*], Melda Putri[1], Retno Dwi Arianty[1]

[1] *Physics Education, Faculty of Teacher Training and Education, University of Riau, Indonesia*

Corresponding author's email: taniasiak01@gmail.com

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Abstract- This study aims to identify light interference patterns in graded-index multimode optical fibers using the Optical Time-Domain Reflectometry (OTDR) method. The optical fiber configuration employed consists of a singlemode-multimode-singlemode (SMS) structure as the measurement medium. This approach enables real-time monitoring of light intensity variations caused by interference phenomena as light propagates through the fiber. Experimental results indicate that the interference pattern is significantly influenced by the light wavelength and the physical structure of the fiber. These effects are reflected in the changes observed in the OTDR reflection graph. The resulting interference patterns illustrate the interaction between different light modes within the multimode fiber. These findings confirm that the OTDR method can serve as an effective, non-invasive technique for analyzing and monitoring optical fiber performance without the need for cutting or splicing. This technique provides an efficient means of early detection of disturbances or performance degradation in optical fibers, potentially enhancing the reliability of optical communication systems across various applications

Keywords: *Optical interference, Optical fiber, Graded index, OTDR reflectometry, SMS structure, Optical fiber monitoring*

1 Introduction

Light interference is an optical phenomenon that occurs when two or more light waves meet and overlap, resulting in a pattern of varying intensity between maximum and minimum. This phenomenon plays an important role in various technological applications, especially in fiber optic-based communication systems. Optical fiber itself is a glass or plastic transmission channel designed to transmit light with high efficiency and very low power loss. In the development of current communication technology, optical fiber is widely used because of its ability to transmit light signals in the form of pulses quickly and stably (Ali & Irawan, 2023). During the process of light transmission in the fiber, interference can occur as a result of changes in the wave phase, which has an impact on the strength of the received signal. This condition can be utilized in various technologies, such as optical sensors and multiplexing systems, because it is very sensitive to physical changes and the surrounding environment.

The singlemode–multimode–singlemode (SMS) configuration structure in optical fiber has been shown to produce distinct interference effects, which are particularly useful in detecting variations in temperature, pressure, and vibration. Furthermore, graded-index multimode fibers have the ability to smooth out light propagation within the fiber core, thereby increasing sensitivity to external interference. One technique used to analyze interference phenomena in optical fiber is Optical Time Domain Reflectometry (OTDR) (Nasir, 2023). This method allows for the measurement of variations in light reflection intensity along the fiber length, allowing for accurate detection of the location and type of interference.

OTDR has become a widely used method because it is non-destructive, efficient, and suitable for analyzing the performance of overall fiber systems. Therefore, the interference of light waves in optical

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fibers is not only an important subject of physics but also offers great potential for innovation in optical communication and sensor technology. A thorough understanding of this phenomenon is essential for improving the performance of modern optical systems and developing technological solutions that are responsive to current and future needs.(Hodgkinson, 1979)

2 Research Methodology

Light interference is the phenomenon of the superposition of two or more overlapping light waves, producing an intensity pattern consisting of bright (constructive) and dark (destructive) regions. In the context of optical fibers, interference occurs due to phase differences resulting from variations in the light path length and the refractive index of the medium. The mathematical relationship of interference intensity can be explained by(Jacsó, 2007):

$$\mathrm{I} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\delta) \quad (2.1)$$

I is the total intensity of the light produced. I_1 and I_2 are the intensities of each light wave. $\Delta\varphi$ is the phase difference between the waves. Where is the phase difference that depends on the optical path length and the wavelength:

$$\Delta\delta = \left(\frac{2\pi}{\lambda}\right) \cdot \Delta L \quad (2.2)$$

$\Delta\varphi$ is the phase difference between two waves. λ is the wavelength of light. ΔL is the difference in optical path length. Interference is crucial in the development of optical sensors due to their sensitivity to environmental disturbances such as temperature, pressure, and strain. Any change in the fiber structure causes a shift in the interference pattern, which can be measured and analyzed.(Yasin, 2016).

Optical Fiber Structure in Interference

The most common fiber type used in interference techniques is the Singlemode–Multimode–Singlemode (SMS) configuration. In this structure, light is guided from a single-mode fiber to a multimode fiber, where multiple wave modes are formed and interfere with each other, and then guided back to the single-mode fiber. This mode variation produces an interference pattern that is sensitive to changes in the external environment, such as temperature, pressure, or refractive index.(Wu et al., 2021).

Constructive interference occurs when two light waves meet in phase, while destructive interference occurs when they are 180 degrees out of phase. In optical fibers, this phase control can be achieved by adjusting the fiber length or the ambient temperature.(Born et al._1999, nd).

Multimode fiber with a graded refractive index profile is also used to reduce dispersion and maintain signal consistency. The parabolic refractive index profile in the fiber core minimizes the speed difference between light modes, ultimately improving the accuracy of interference pattern formation.(K. Thyagajan, 1995).

In optical fiber, light not only propagates in a straight line, but can also undergo multiple total internal reflections. Due to the different path lengths between the core and cladding, or between modes in a multimode fiber system, interference occurs between the waves.(Kumar & Shao, 2016).

Two types of interference that often appear in optical fiber(McCool, 2019):

1. Intermodal interference: occurs in multimode fiber. Because light travels in multiple modes at different speeds, there will be differences in travel time that cause interference between signals.

2. Interference in fiber-optic interferometers: These devices utilize the interference of light in fibers to detect changes in refractive index or physical deformation. An example is the fiber-optic Mach-Zehnder interferometer.

OTDR Technique and Analysis Process

In fiber-optic research, the Optical Time Domain Reflectometry (OTDR) method is often used to observe interference response. This technique utilizes the reflection of light signals from faults or splices along the optical fiber. The fiber length can be calculated from the light travel time and propagation speed using the formula(Jacsó, 2007):

$$L = \frac{v \cdot t}{2} \ atau \ v = \frac{c}{n} \quad (2.3)$$

L is the length of the optical fiber. v is the speed of light in the fiber. t is the travel time of the reflected signal. c is the speed of light in a vacuum. n is the refractive index of the optical fiber. Where is the speed of light in a vacuum and is the refractive index of the fiber. OTDR results are usually visualized as a graph of intensity versus distance or time, which shows the reflection of light at specific points in the fiber.

The Fabry–Pérot structure is also used to create interference at the end of an optical fiber by utilizing two parallel reflective surfaces that produce a resonance of light between them.(John, 2011)Interference in optical fibers is strongly influenced by the wavelength of the light. Coherent light sources such as lasers are used to stabilize the interference and allow for accurate analysis.(Chu, 2013).

Interference modes in optical fibers can be used as the basis for sensing systems to measure micro-changes in environmental parameters, including gas concentrations and human blood pressure.(Teng et al., 2008).

Analysis and Conclusion Stage

All data from the literature were analyzed descriptively and qualitatively by comparing findings from various studies. The analysis was conducted to identify general patterns, advantages and disadvantages of the interference method, and its potential application in the field of optical measurement and technology. The credibility of the sources was assessed through publisher reputation, content relevance, and publication recency.(Boyd, 2008).

The phenomenon of interference in optical fiber is not just a theory, but is also applied in various technologies.(Arnaud, 1980):

- Fiber optic sensors: Use interference to detect pressure, temperature, and vibration.
- Fiber-based spectroscopy: Relies on interference to identify the light spectrum of a sample.
- High-precision optical communications: Controlling interference to improve signal integrity.

3 Results and Discussion

Interference in SM Optical Fiber Structures

The analysis results show that the SMS (Singlemode–Multimode–Singlemode) optical fiber configuration is capable of producing a stable interference pattern and is highly sensitive to environmental conditions. As light propagates from a single-mode fiber to a multimode fiber, several transverse modes are generated. Each of these modes has its own path and phase difference, which causes interference when the light is recoupled to the second single-mode fiber.(Hatta et al., 2009).

SMS interference sensors exhibit high sensitivity because their interference patterns change significantly with small changes in the environment. This makes this technology superior in civil and geotechnical engineering.(Measures, & Abrate, 2002).

Intermode interference produces intensity variations that are sensitive to external factors such as temperature, strain, or refractive index variations. These changes are characterized by a shift in the output spectrum. The length of the multimode fiber, its core diameter, and the wavelength used are the main factors influencing the shape and sensitivity of the interference pattern. Simulation and experimental studies have shown that the longer the multimode fiber, the greater the sensor's sensitivity. However, this can reduce resolution unless balanced by an adequate signal processing system.(Wu et al., 2021).

In real-time monitoring systems, SMS configurations are often combined with Optical Time Domain Reflectometry (OTDR) techniques. OTDRs allow spatial mapping of light reflection intensity along the fiber and detect fault locations or anomalies based on changes in the interference pattern. When combined, SMS and OTDR structures can be used to build large-scale temperature or strain distribution measurement systems.(Hartog, 2017).

The performance of an SMS system also depends on design factors such as the length of the multimode fiber, the refractive index profile (e.g., graded index), and the type and stability of the light source. The use of a coherent laser with a fixed wavelength improves the spatial and temporal coherence of the light, making the resulting interference clearer and easier to analyze. This technology is the foundation for future optical sensors that are more responsive, stable, and digitally integrated with other smart devices.(Hecht, 2006).

The integration of SMS systems with digital technologies such as IoT and artificial intelligence is now a new development direction in the optical field. Interference-based sensors are capable of generating large amounts of data with high sensitivity, and automated data processing by AI enables early detection of structural anomalies and environmental changes. This combination makes SMS systems not only measurement instruments but also part of data-driven decision-making systems.(L. Zhao et al., 2020).

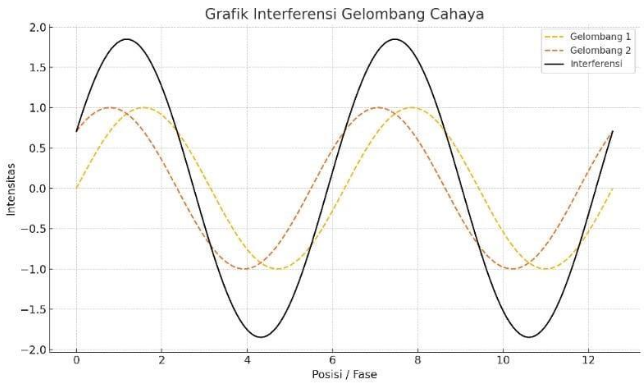

Figure 1: Interference pattern of two sinusoidal light waves

Response to Physical Changes

Interference in optical fibers is highly sensitive to external physical disturbances because the propagation properties of light in the fiber medium are highly dependent on parameters such as the optical path length and refractive index. When physical changes such as mechanical strain, temperature, or pressure occur, these parameters change, triggering a phase difference between the propagating light wave modes. This phase difference then produces a new interference pattern at the output end of the optical fiber. Because the phase change is linear with the path length and refractive index, interference-based systems are well-suited for use as sensors to detect even small disturbances.(Agrawal, 2021).

Temperature change is one of the most significant physical factors affecting interference in optical fiber structures. As temperature increases, thermal expansion occurs in the fiber, which causes an increase in the light path length. Furthermore, the refractive index of glass also changes with temperature, known as the thermal optical effect. The combination of these effects causes a phase shift between light waves in multimode fibers, resulting in a shift in the interference spectrum. Sensors based on the Singlemode–Multimode–Singlemode (SMS) configuration are known to have a sensitivity of ±0.1 nm/°C in detecting wavelength changes due to temperature.(Chen et al., 2004).

In addition to temperature, mechanical strain also has a significant impact on the interference response in optical fibers. When a fiber is stretched or compressed, its geometric length changes, which directly alters the optical path length of the propagating light wave. This causes a phase change that is detected as a shift in the interference peaks. Interference-based sensors are ideal for strain measurement because their response is fast, linear, and unaffected by electromagnetic fields. This application has been widely used in monitoring systems for bridges, tall buildings, and dams.(Kersey et al., 1997).

External pressure applied to a fiber can also change the optical field distribution within the fiber core and cladding, thus affecting the light mode profile. Pressure changes cause deformation of the fiber's microstructure, which changes the local refractive index and results in a change in the interference pattern. In some applications, interference-based optical sensors are used to detect the pressure of liquids, gases, and even human blood pressure with great accuracy. These systems are highly relied upon in the biomedical world due to their high reliability and small size.(Z. Zhao et al., 2022). The interference phenomenon is influenced by the effective optical path length of each mode, which can be expressed as:

$$OPL = n \cdot L \qquad (3.1)$$

*OPL*is the effective optical path length. n is the refractive index of the medium. L is the physical length of the fiber. where is the refractive index of the material and is the fiber length. Temperature changes affect both of these variables, resulting in a change in the phase difference between modes, resulting in a new interference pattern. The phase change is expressed as:

$$\Delta\emptyset = \frac{2\pi}{\lambda} \cdot \Delta(nL) \qquad (3.2)$$

Δφ is the phase difference due to length change. n is the refractive index. ΔL is the change in fiber length due to strain or temperature. λ is the wavelength of light. SMS-based sensors have a wavelength sensitivity of approximately ±0.1 nm/°C, depending on the optical configuration. In addition to temperature, strain also affects interference by mechanically changing the fiber length. This makes SMS sensors ideal for deformation measurement applications or monitoring engineering structures.(Ascorbe et al., 2021).

Visualizing Interference Patterns with an OTDR

Optical Time Domain Reflectometry (OTDR) techniques are used to monitor the characteristics of light reflection in fiber. When used in conjunction with an SMS system, an OTDR can display intensity changes due to interference as a distance versus reflection intensity graph. The recorded reflection pattern illustrates the phase shift and location of the interference. Integrating an OTDR with an SMS structure allows for remote sensor monitoring with high accuracy, even over fiber lengths reaching hundreds of meters. OTDR data is crucial for detecting the location of interference or changes in physical parameters such as local strain and temperature variations in real time.(Senior & Jamro, 2007).

Advantages of Fiber Optic Interference System

When compared with other optical sensor technologies such as gratings or resonators, the SMS system has a number of advantages.(Ghatak & Thyagarajan, 1998):

- The structure is simple and inexpensive, as it does not require additional reflective elements.
- Flexible design: multimode fiber length and coupling type can be customized.
- Resistant to electromagnetic interference, because the working principle is based on light

However, this system still has challenges, especially in maintaining the stability of interference signals and the need for periodic recalibration for high accuracy.

Applications and Development

The potential applications of SMS-based interference sensors are extensive. In industry and civil engineering, these systems can be used for structural monitoring, pressure measurement, or vibration detection. In the medical field, interference-based sensors are also beginning to be used in optical blood pressure or heart rate monitoring devices. Advances in signal processing technology and the incorporation of methods such as Fourier transform or multiplexing can significantly improve the accuracy and sensitivity of these systems.(Mir, 2017).

In the energy industry, particularly the oil and gas sector, interference sensors are used to detect pressure and temperature in drilling wells and subsea pipelines. These sensors' resistance to extreme conditions and corrosion makes them ideal for safe and precise monitoring of oil and gas distribution. In nuclear power plants, these systems are even used to monitor critical parameters in high-radiation environments without being disturbed by EMI.(Liu et al., 2023).

The use of interference is also growing in security and defense, such as in fiber-optic perimeter surveillance systems. Sensors embedded in fences, floors, or walls respond to any unusual vibrations or contact by changing their interference patterns. These systems have been widely adopted for securing airports, military facilities, and national borders because they can provide early warning without being visible to the naked eye.(Hatta et al., 2013).

Materials development is also a major focus, with photonic crystal fibers (PCFs) and hollow-core fibers now being used to produce more stable and selective interference. These microstructures enable more precise control of light modes, improve sensor sensitivity, and expand applications to the fields of quantum mechanics, optomechanics, and integrated photonics.(Kirchhof et al., 2006).

With these advances, interference in optical fibers is no longer just a part of measurement and communication systems, but has become a key technology in shaping a globally connected, adaptive, and data-driven ecosystem of intelligent sensors. The future of these systems lies in the complementary integration of physics, electrical engineering, information technology, and artificial intelligence.(Lee et al., 2009)

4. Conlusions

From the results of the studies and analyses conducted, it can be stated that the principle of light interference in the SMS (Singlemode–Multimode–Singlemode) type optical fiber configuration has great potential in the development of efficient and accurate optical sensor systems. The interference process is formed when light waves propagating through several modes in a multimode fiber are coupled back to a singlemode fiber, producing an intensity pattern that is sensitive to various external disturbances such as temperature changes, mechanical strain, pressure, and refractive index fluctuations. The shape and sensitivity of the resulting interference pattern are strongly influenced by the structural parameters of the fiber, such as the length and diameter of the multimode fiber core, as well as the characteristics of the light source used. The phase shift between modes as a result of environmental variations creates a spectrum change that can be used as a measurement signal.

Optical Time Domain Reflectometry (OTDR) provides additional capabilities for detecting these changes spatially, displaying information as a graph of intensity versus distance. Compared with other optical sensor technologies, SMS-based sensors offer several advantages: simple design, low cost, flexibility in fabrication, and resistance to electromagnetic interference. However, challenges remain in maintaining the stability of the interference pattern and the need for a signal processing system to improve measurement accuracy.

Overall, this fiber-optic interference system demonstrates promising performance in various applications, such as infrastructure monitoring, strain detection in buildings, biomedical sensors, and industrial control systems. Further research can be directed at developing more sensitive fiber configurations, multiplexing techniques for multiparameter monitoring, and integration with digital systems to produce more adaptive and multifunctional sensor devices.

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