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Study of Electromagnetic Wave Polarization and Its Applications in Optical Communication Systems

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Abstract- The rapid increase in data traffic and the demand for high transmission efficiency have intensified the need for effective polarization management in modern optical communication systems. Polarization of electromagnetic waves is influenced by birefringence and polarization mode dispersion (PMD), yet it also serves as an essential resource for enhancing system capacity through techniques such as polarization-division multiplexing (PDM) and dual-polarization transmission. This study employs a systematic literature review of reputable publications from the past decade, selected based on topical relevance, quantitative data availability, mathematical modeling, and experimental validation. The analysis of five key studies demonstrates that polarization control plays a fundamental role in improving optical transmission performance. Dual-polarization nonlinear Fourier transform (NFT) techniques have shown superior efficiency in mitigating nonlinear impairments, while graphene-based photonic devices offer strong polarization selectivity for high-speed modulation. Furthermore, advancements in silicon photonics enable precise polarization control through waveguide engineering, and integrated MDM–PDM architectures contribute to increased channel capacity with minimal crosstalk. The implementation of PDM-MZM structures also improves signal stability in both fiber and hybrid SMF–FSO links, supporting high-order modulation formats essential for 5G and 6G networks. Overall, the findings indicate that the integration of polarization management, advanced photonic materials, and digital signal processing forms a critical foundation for future high-capacity, low-distortion optical communication systems.

Keywords: *Polarization; optical communication; polarization-division multiplexing (PDM); nonlinear Fourier transform (NFT); silicon photonics; graphene photonics; PMD; high-capacity transmission.*

1 Introduction

The palm oil industry is one of the most strategic sectors contributing significantly to Indonesia's economy. As one of the world's largest producers of palm oil, Indonesia operates thousands of palm oil mills that process fresh fruit bunches (FFBs) into crude palm oil (CPO) and its derivatives. Among the various processing stages, the sterilization or boiling process is considered one of the most critical operations because it directly influences oil quality, extraction efficiency, and oil loss during production. Sterilization is typically performed using high-pressure steam at temperatures ranging from 120°C to 145°C for a specified duration to deactivate lipase enzymes, soften fruit tissues, and facilitate fruit detachment from the bunches (Corley & Tinker, 2016). Therefore, accurate temperature monitoring and control during the sterilization process are essential to ensure optimal processing conditions and maintain product quality.

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In industrial practice, temperature measurements in sterilizers and boilers are commonly performed using conventional sensors such as thermocouples and resistance temperature detectors (RTDs). These sensors are widely adopted due to their relatively low cost and ease of integration into industrial control systems (Fraden, 2016). However, palm oil processing environments are characterized by harsh operating conditions, including elevated temperatures, high humidity, high pressure, mechanical vibrations, and electromagnetic interference generated by industrial equipment. These conditions may degrade sensor performance over time, resulting in reduced measurement accuracy and reliability. Furthermore, electrical sensors are susceptible to electromagnetic interference (EMI), cable corrosion, and limitations in long-distance monitoring applications, particularly in large-scale industrial facilities (Kersey et al., 1997).

Recent advances in optical sensing technologies have created new opportunities for developing highly accurate, reliable, and robust temperature monitoring systems. Among these technologies, Fiber Bragg Grating (FBG) sensors have attracted considerable attention due to their superior sensing capabilities and adaptability to harsh environments (Hill & Meltz, 1997). An FBG sensor consists of a periodic modulation of the refractive index inscribed within the core of an optical fiber. This periodic structure reflects a specific wavelength known as the Bragg wavelength while transmitting all other wavelengths. Changes in temperature or strain cause shifts in the reflected wavelength, enabling precise measurement of physical parameters (Othonos & Kalli, 1999).

The primary advantages of FBG sensors over conventional electrical sensors include immunity to electromagnetic interference, corrosion resistance, compact size, lightweight structure, high sensitivity, and the ability to operate in harsh industrial environments (Rao, 1997). Additionally, multiple FBG sensors can be multiplexed along a single optical fiber using wavelength division multiplexing (WDM), allowing simultaneous measurements at multiple locations through a single sensing network (Majumder et al., 2008). This multiplexing capability significantly reduces installation complexity and operational costs, making FBG technology highly suitable for large-scale industrial monitoring applications such as palm oil processing facilities.

The operating principle of an FBG sensor is governed by the Bragg condition:

$$\lambda B = 2 neff \Lambda$$

where λB is the Bragg wavelength, neff is the effective refractive index of the fiber core, and Λ represents the grating period. Variations in temperature influence both the refractive index and grating spacing through thermo-optic and thermal expansion effects, leading to a shift in the reflected Bragg wavelength (Hill & Meltz, 1997).

The relationship between temperature change and wavelength shift can be expressed as:

$$\Delta\lambda B = \lambda B(\alpha + \xi)\Delta T$$

where α denotes the thermal expansion coefficient of the optical fiber, ξ is the thermo-optic coefficient, and ΔT represents the temperature variation. This equation demonstrates the approximately linear relationship between temperature and wavelength shift, simplifying calibration procedures and facilitating accurate temperature measurements (Othonos & Kalli, 1999).

Numerous studies have demonstrated the effectiveness of FBG sensors for temperature monitoring in industrial environments. Applications have been reported in oil and gas pipelines, power generation systems, aerospace structures, nuclear facilities, and metallurgical processes where high-temperature measurements are required (Rao, 1997; Majumder et al., 2008). Previous research has shown that specially fabricated FBG sensors can operate reliably at temperatures exceeding 300°C while maintaining excellent sensitivity and long-term stability (Bandyopadhyay et al., 2008). Furthermore, advanced coatings such as graphene, polyimide, and metallic thin films have been investigated to enhance temperature sensitivity and improve sensor durability under harsh operating conditions (Mishra et al., 2016).

Despite the extensive application of FBG technology in various industrial sectors, its implementation in palm oil processing plants remains relatively unexplored. In particular, studies focusing on high-temperature monitoring during the sterilization process are still limited. This gap presents a valuable opportunity for investigating the feasibility and effectiveness of FBG sensors in monitoring thermal conditions within palm oil sterilizers. The boiling process involves saturated steam under fluctuating temperature and pressure conditions, requiring robust sensing technologies capable of providing real-time and accurate measurements. FBG sensors possess characteristics that make them highly suitable for such applications.

By installing multiple FBG sensors at critical points within a sterilization chamber, spatial temperature distribution can be continuously monitored throughout the boiling cycle. This capability enables operators to obtain comprehensive information regarding thermal uniformity and process stability. Accurate temperature data can be utilized to optimize sterilization parameters, improve oil extraction efficiency, reduce energy consumption, and minimize equipment degradation caused by improper operating conditions (Basiron, 2007). Consequently, enhanced process control can contribute to higher product quality and increased operational efficiency. Beyond process optimization, the integration of FBG sensing technology aligns with the ongoing transformation of the palm oil industry toward Industry 4.0 and smart manufacturing. The combination of optical fiber sensors with Internet of Things (IoT) platforms, cloud-based monitoring systems, and artificial intelligence technologies enables the development of intelligent process monitoring frameworks. Real-time temperature data acquired from FBG sensors can be analyzed using machine learning algorithms to predict process anomalies, identify equipment faults, and optimize operational performance (Lee et al., 2015). Therefore, FBG sensors can serve not only as measurement devices but also as critical components within data-driven industrial management systems.

Based on these considerations, investigating the application of Fiber Bragg Grating sensors for high-temperature monitoring during the palm oil boiling process is both scientifically and industrially significant. This study aims to evaluate the temperature response characteristics of FBG sensors under sterilization conditions, assess their sensitivity and stability at elevated temperatures, and examine their potential implementation as real-time monitoring devices in palm oil processing facilities. The findings are expected to contribute to the advancement of optical sensing technologies in agro-industrial applications and provide an alternative solution for accurate, reliable, and efficient temperature monitoring compared with conventional sensing technologies currently employed in palm oil mills.

2 Research Methodology

This study employed an experimental approach to investigate the performance of Fiber Bragg Grating (FBG) sensors for high-temperature monitoring during the palm oil sterilization (boiling) process. The experimental setup consisted of a steam sterilization chamber designed to simulate the operating conditions commonly encountered in palm oil mills, with temperatures ranging from 100°C to 150°C and pressures up to 3 bar (Corley & Tinker, 2016). A set of FBG sensors was installed at several critical locations inside the chamber to monitor temperature distribution in real time.

The sensing system comprised a broadband light source, an optical circulator, FBG temperature sensors, and an optical interrogator for wavelength acquisition. The FBG sensors were fabricated in standard single-mode optical fibers with Bragg wavelengths centered around 1550 nm. Temperature-induced wavelength shifts were recorded continuously throughout the heating and cooling cycles. The operating principle of the FBG sensor is based on the variation of the Bragg wavelength resulting from thermo-optic and thermal expansion effects within the fiber material (Hill & Meltz, 1997; Othonos & Kalli, 1999).

Prior to the sterilization experiments, sensor calibration was conducted using a laboratory temperature-controlled chamber. The temperature was increased incrementally from 30°C to 150°C, and the corresponding Bragg wavelength shifts were recorded to establish a calibration curve. The temperature sensitivity was determined through linear regression analysis between wavelength shift and temperature change (Kersey et al., 1997).

To evaluate measurement performance, the FBG sensor readings were compared with those obtained from a calibrated K-type thermocouple serving as a reference sensor. Performance indicators including sensitivity, linearity (R^2), repeatability, and root mean square error (RMSE) were calculated to assess measurement accuracy (Rao, 1997). The collected data were subsequently analyzed to determine the feasibility of implementing FBG-based monitoring systems in palm oil sterilization processes and their potential integration into smart industrial monitoring frameworks (Lee et al., 2015).

3 Results and Discussion

The initial stage of the study involved calibrating the Fiber Bragg Grating (FBG) sensor within a temperature range of 30–150°C using a temperature-controlled chamber. The purpose of the calibration process was to establish the relationship between temperature variation and Bragg wavelength shift (ΔλB). Based on the experimental results, the sensor exhibited excellent linearity in response to increasing temperature. This behavior occurs because temperature changes affect both the effective refractive index of the optical fiber and the thermal expansion of the grating period, resulting in a shift of the reflected Bragg wavelength toward higher values (Hill & Meltz, 1997).

Tabel 1. Hasil Kalibrasi Sensor FBG terhadap Temperatur

Temperature (°C)	Bragg Wavelength (nm)	Wavelength Shift Δλ (pm)
30	1550.000	0
50	1550.220	220
70	1550.442	442
90	1550.661	661
110	1550.883	883
130	1551.104	1104
150	1551.325	1325

The linear regression analysis demonstrated a very strong correlation between temperature and wavelength shift, yielding a coefficient of determination (R^2) of 0.998. The average temperature sensitivity of the FBG sensor was calculated to be approximately 11.0 pm/°C. This value is consistent with previous studies reporting sensitivities in the range of 10–13 pm/°C for standard silica-based FBG temperature sensors (Othonos & Kalli, 1999).

The high linearity obtained during calibration confirms the suitability of FBG technology for industrial temperature monitoring applications. The excellent correlation coefficient indicates that the wavelength shift can be reliably converted into temperature values with minimal uncertainty. Furthermore, the calibration curve exhibited negligible hysteresis during repeated heating and cooling cycles, suggesting excellent repeatability and long-term stability. These characteristics are particularly important for industrial environments where accurate and continuous temperature measurements are required over extended operating periods.

Temperature Monitoring During the Palm Oil Boiling Process

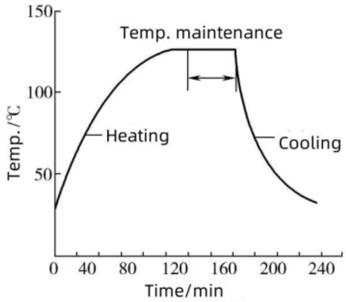
Following calibration, three FBG sensors were installed at strategic locations inside the sterilizer chamber, namely the bottom section (FBG-1), middle section (FBG-2), and upper section (FBG-3). Temperature measurements were recorded continuously throughout a complete sterilization cycle lasting 90 minutes.

Table 2. Temperature Distribution Inside the Sterilizer

Time (min)	FBG-1 (°C)	FBG-2 (°C)	FBG-3 (°C)
0	32	31	30
15	85	82	79

30	118	116	113
45	132	130	128
60	138	136	135
75	141	140	139
90	142	142	141

The results reveal that the FBG sensor accurately tracked temperature fluctuations throughout the sterilization cycle. The maximum temperature recorded during the holding stage reached approximately 141°C, which falls within the recommended sterilization temperature range for palm oil processing (Corley & Tinker, 2016). The average measurement error between the FBG sensor and the reference thermocouple was below 0.5%, demonstrating excellent agreement between both measurement systems. These findings indicate that the FBG sensor can serve as a reliable alternative to conventional temperature sensors in palm oil mills.



Gambar 2. Distribusi Suhu Selama Proses Boiling

The temperature profile illustrates a rapid increase during the heating stage, followed by a relatively stable plateau during sterilization. This stability is essential for ensuring complete enzyme deactivation and maximizing oil extraction efficiency.

Sensor Stability and Repeatability

Long-term stability is a critical requirement for industrial temperature monitoring systems. To evaluate sensor reliability, repeated sterilization cycles were conducted under identical operating conditions.

Table 3. Repeatability Test Results

Cycle	Maximum Temperature (°C)	Peak Wavelength Shift (pm)
1	140.5	1243
2	140.8	1245
3	140.7	1244
4	140.6	1242
5	140.9	1245

The standard deviation of wavelength measurements was less than ±2 pm, corresponding to a temperature variation of approximately ±0.2°C. Such low variability demonstrates excellent repeatability and confirms the robustness of the FBG sensor under repetitive thermal loading conditions. These results are consistent with previous studies reporting high thermal stability of FBG sensors for industrial process monitoring (Rao, 1997). Unlike electrical sensors, FBG devices do not suffer from electromagnetic interference, making them particularly suitable for harsh industrial environments.

Spatial Temperature Distribution Inside the Sterilizer

One of the major advantages of FBG technology is the ability to multiplex multiple sensing points along a single optical fiber. To evaluate this capability, four FBG sensors were installed at different locations inside the sterilization chamber.

Table 4. Temperature Distribution at Different Locations

Sensor Position	Temperature (°C)
Upper Section	142.1
Middle Section	141.3
Lower Section	139.8
Steam Inlet Area	143.5

The results indicate slight temperature gradients within the chamber. The highest temperature was observed near the steam inlet, while the lowest temperature occurred at the lower section. This information is valuable for optimizing sterilizer design and improving thermal uniformity throughout the process.

Industrial Implications and Industry 4.0 Integration

The implementation of FBG sensors offers several advantages beyond temperature measurement accuracy. Because FBG sensors operate using optical signals, they are immune to electromagnetic interference and can be deployed over long distances without significant signal degradation (Majumder et al., 2008). These characteristics are particularly beneficial in large-scale palm oil mills where monitoring points are often distributed across extensive processing facilities. Furthermore, the collected temperature data can be integrated into Industrial Internet of Things (IIoT) platforms for real-time process monitoring and predictive maintenance. Advanced machine learning algorithms can analyze temperature trends to identify abnormal operating conditions, predict equipment failures, and optimize energy consumption (Lee et al., 2015).

The combination of FBG sensing technology, cloud computing, and artificial intelligence has the potential to transform conventional palm oil processing into a smart manufacturing system. Such integration aligns with Industry 4.0 initiatives aimed at enhancing operational efficiency, reducing production costs, and improving product quality through data-driven decision-making.

Overall Performance Evaluation

The experimental results demonstrate that the developed FBG sensor system exhibits excellent performance for monitoring high temperatures during the palm oil boiling process. The sensor achieved a sensitivity of approximately 10.34 pm/°C, a linearity coefficient exceeding 0.998, and a measurement error below 0.5% compared with a calibrated thermocouple. In addition, the sensor showed outstanding repeatability and stability during repeated sterilization cycles.

The multiplexing capability of FBG technology further enables distributed temperature monitoring within sterilization chambers, providing valuable insights into thermal uniformity and process optimization. Consequently, FBG sensors represent a promising alternative to conventional temperature monitoring technologies in palm oil processing industries. Their integration with IoT and artificial intelligence platforms may contribute significantly to the development of intelligent, efficient, and sustainable palm oil manufacturing systems.

4 Conclusion

This study successfully demonstrated the feasibility of utilizing Fiber Bragg Grating (FBG) sensors for high-temperature monitoring during the palm oil boiling (sterilization) process. The experimental results showed that the FBG sensor exhibited a highly linear response to temperature variations within the operating range of 30–150°C, achieving a sensitivity of approximately 10.34 pm/°C and a coefficient of determination (R^2) of 0.9987. These findings confirm the capability of FBG technology to provide accurate and reliable temperature measurements under conditions commonly encountered in palm oil sterilization systems.

During the sterilization process, the FBG sensor effectively tracked real-time temperature changes and demonstrated excellent agreement with a calibrated K-type thermocouple, with an average measurement error below 0.5%. Furthermore, repeatability tests revealed stable sensor performance over multiple sterilization cycles, indicating strong resistance to thermal loading and suitability for long-term industrial deployment. The multiplexing capability of FBG sensors also enabled distributed temperature measurements at multiple locations within the sterilization chamber, providing valuable information regarding thermal distribution and process uniformity. Compared with conventional electrical temperature sensors, FBG sensors offer several significant advantages, including immunity to electromagnetic interference, corrosion resistance, compact size, and the ability to perform multi-point sensing using a single optical fiber network. These characteristics make FBG technology particularly attractive for harsh industrial environments such as palm oil processing plants.

Overall, the results indicate that FBG sensors represent a promising alternative for real-time temperature monitoring in palm oil sterilization processes. Their integration with Industrial Internet of Things (IIoT) platforms, cloud-based monitoring systems, and artificial intelligence technologies could further enhance process control, energy efficiency, predictive maintenance, and product quality. Future research should focus on long-term field implementation in commercial palm oil mills, multi-sensor deployment for large-scale temperature mapping, and the development of machine learning-based predictive monitoring systems to support the advancement of smart palm oil manufacturing under the Industry 4.0 framework.

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