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Comparative analysis of different fiber types for strain sensing application under simulated mine conditions

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ABSTRACT

The recent advances in technology have provided deeper insights into hazard detection for mine safety. This study proposes an optical fiber sensor for mining applications. The performance of four fiber types—G652 Corning, G655 OFS, G655 Corning, and PMF Corning—was evaluated when subjected to controlled strain, simulating potential failure conditions. Additionally, the effectiveness of three laser sources—DFB, MZM, and WDM—was assessed to determine the most suitable laser for strain sensing. Constant input powers were used for strain measurements (Fig. 2), with the power recovering to approximately the same values after unloading (Fig. 3), confirming that no permanent deformation occurred in the fibers. In contrast, a fixed input power of 0.49 dBm was maintained across each of the three laser sources during performance evaluation (Fig. 4to ensure consistency in the comparisons. The optimal combination of the MZM laser source and G655 OFS fiber was found to be the best for mining applications. A strain sensitivity of 0.0041 dB/N and an SOP speed of 5.125 ^{0}/s is achieved. The data obtained from these experiments offer valuable insights into the behaviour of mine structures under stress and can contribute to the development of reliable early warning systems.

1. Introduction

Mining, a critical industry for extracting minerals and resources, involves inherent risks, among which mine collapses are very dangerous. Mine collapses, also referred to as ground failures or subsidence, occur when the underground support structures fail, leading to sudden and often catastrophic ground movements. Such incidents can result in the loss of life, injury, and significant economic damage. The causes of mine collapse are multifaceted, including factors like geological instability, over-extraction of minerals, structural failures, and water infiltration (Hustrulid and Bullock, 2001). Geological factors contributing to mine collapses include the presence of fault lines, unstable rock formations, and variation in rock strength (Chandarana et al., 2016; Kolapo et al., 2022). Operational practices, such as excessive extraction or inadequate ground support, can exacerbate these risks (Bansah et al., 2016; Galvin and Galvin, 2016; Chu and Muradian, 2016). For instance, the removal of large volumes of ore can lead to significant stress on the surrounding rock, increasing the likelihood of collapse. Moreover, poor design of support systems and inadequate monitoring of geological conditions can further compound these risks (Galvin and Galvin, 2016).

Effective hazard detection and management are crucial for mitigating the risks associated with mine collapses. Early detection systems aim to identify potential structural failures before they result in catastrophic events. Traditional methods, such as visual inspections and manual measurements, are often limited in scope and accuracy. Consequently, there is a growing need for advanced technologies that can provide real-time, precise monitoring of mine conditions.

Fiber optic technology has emerged as significant advancement in hazard detection due to its ability to offer high resolution, continuous monitoring of physical changes within mining environments (Reddy et al., 2016; Ranjan et al., 2016; Kumar, 2016). Optical fibers can be employed as sensing elements to monitor various parameters such as strain, temperature, and vibration (Liu et al., 2016; Morshed and El-Sayed, 2016; Masoudi and Newson, 2016; Barrias et al., 2016; Schena et al., 2016). When used for strain detection, optical fibers respond to physical forces applied to them, such as those experienced during mine collapse, by altering the transmitted light signal (Mollahasani, 2016). Optical fiber sensors can be embedded within the mine infrastructure or placed along tunnels to detect changes indicative of potential collapses

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(Wijaya et al., 2021; Zhang et al., 2024). The use of fiber optic sensors offers several advantages for early hazard detection. They provide continuous, real-time monitoring over long distances, are highly sensitive to minute changes, and are immune to electrically noisy environments typical for mining operations (Sabri et al., 2015; Gholamzadeh and Nabovati, 2008; Udd and Spillman, 2024; Culshaw, 2000). These features enable more accurate predictions of potential collapses and facilitate timely interventions to prevent disasters.

Our experimental work, which involves applying controlled masses to optical fibers to simulate strain conditions, is aimed at enhancing the understanding of how strain affects mining structures. By, replicating the stress conditions associated with mine collapses, this research contributes to the development of more effective monitoring systems and safety protocols.

This paper is arranged as follows, first is the introduction, followed by research design, then results and discussion, and conclusive remarks.

2. Methodology

The experimental setup employed in this study is shown in Fig. 1). The objective of the experiment was to evaluate the sensitivity of different optical fibers to strain, simulating conditions similar to a mine collapse. To achieve this, a DFB laser source operating at a wavelength of 1550 nm, was used to inject light into four types of optical fibers: G652 Corning, a standard single-mode fiber; G655 OFS a single-mode fiber with specific dispersion properties; G655 Corning, similar to G655 OFS but from different manufacturer; and Polarization Maintaining Fiber (PMF), which maintains light polarization. All the four fiber types under investigation were of the same length of 3 m, each spliced at the ends. Each fiber's sensitivity to strain was carefully measured by applying controlled loads and monitoring the resulting power fluctuations. The choice of a 3 m fiber length was motivated by the need to maintain experimental control while ensuring representative strain response. In fiber optic strain sensing, it is well established that any localized perturbation along the fiber can induce optical attenuation detectable at the receiver, due to mechanisms such as micro-bending and mode coupling (Masoudi and Newson, 2016; Gardner, 1975). This behaviour

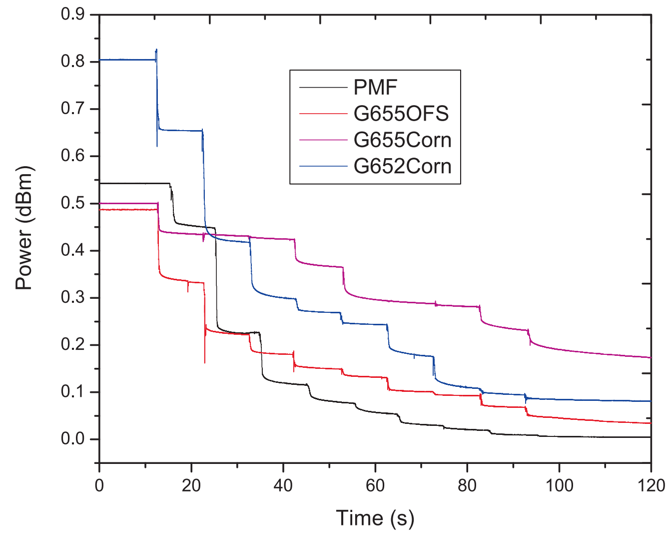

Fig. 2. Fiber response to incremental 2 kg load up to 18 kg at 10-second time interval.

remains consistent over extended fiber lengths, enabling strain detection even in kilometre-scale deployments (Udd and Spillman, 2024; Culshaw and Kersey, 2008). Therefore, testing on a 3 m segment does not limit the relevance of the results; rather, it enables detailed, high-resolution observation of strain effects while preserving the scalability of the sensing mechanism. Longer lengths would have increased experimental complexity without providing additional insight into localized strain behaviour under controlled loading.

In this study, bare optical fibers were intentionally used to enable direct evaluation of their intrinsic strain sensing characteristics under controlled laboratory conditions. The approach allows for clear understanding of optical attenuation behaviour as a function of mechanical strain, without the influence of jacketing layers. While the setup does not replicate the exact conditions of field deployment in mining

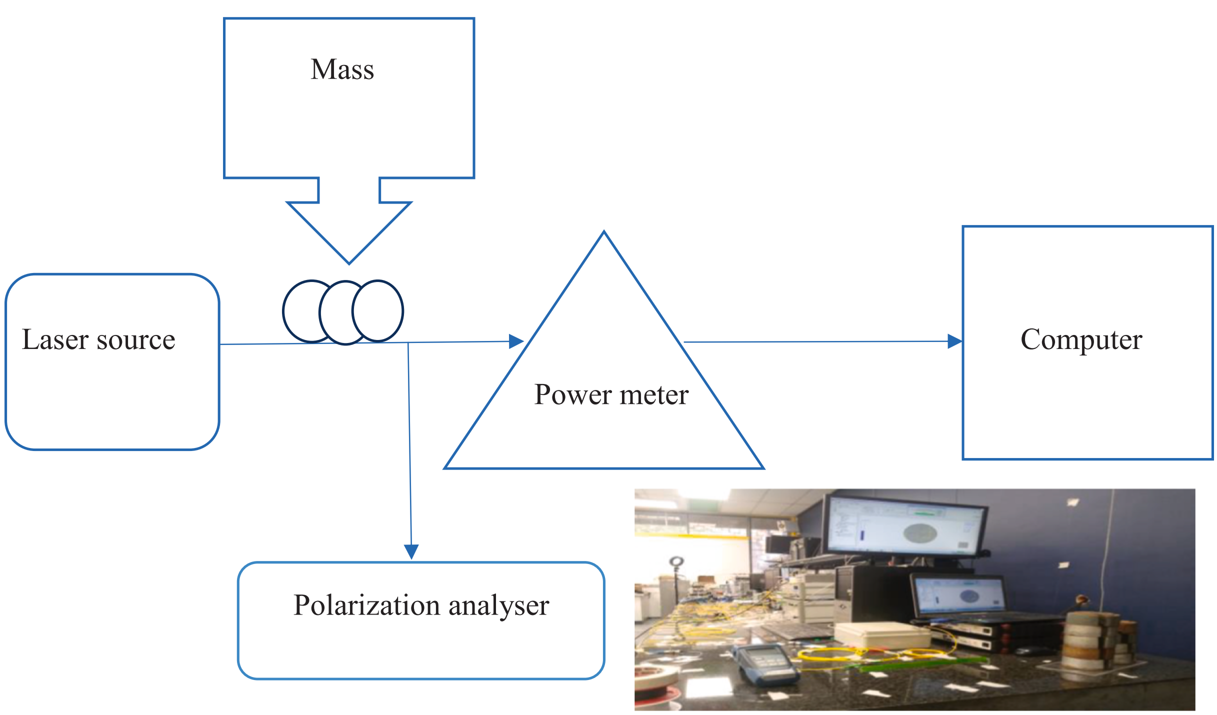

Fig. 1. Experimental setup for evaluating the effectiveness of various laser sources and fiber types to simulated strain conditions of a mine collapse. Inset: Picture showing actual fiber clamping using the smooth plastic fixture described.

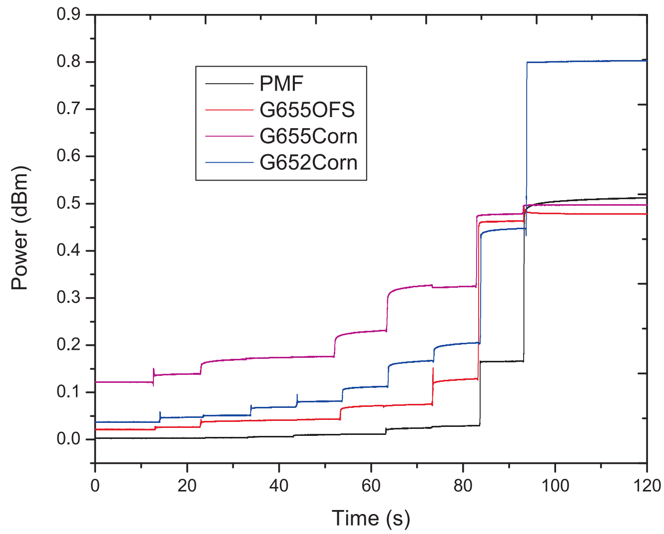

Fig. 3. Fiber response during unloading of masses.

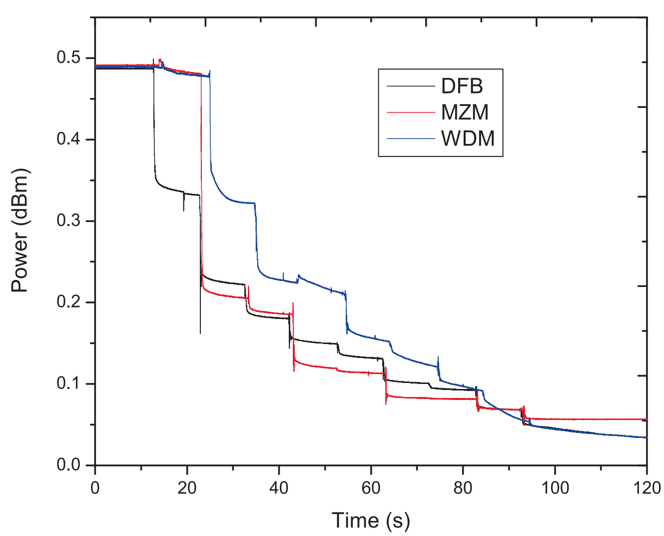

Fig. 4. Laser sources performance operating at 1550 nm on a G655 OFS fiber.

environments – where fibers are typically housed in ruggedized cables – it provides a fundamental baseline for understanding how different fiber types respond to strain. These findings are intended to inform the design and selection of more robust cable – based fiber optic sensing systems in future work.

A section of each fiber was subjected to controlled strain by applying incremental loads. Specifically, 2 kg masses were added at 10 s intervals until a total of 18 kg was reached. The applied mechanical load ranged incrementally up to 18 kg, was selected not to simulate the magnitude of forces during mine collapse but to provide controlled, repeatable range for observing and comparing strain sensitivity among different fiber types. This 18 kg also was dictated by the nature of fragile glass fiber. The primary goal was to evaluate the ability of the optical fibers to detect incremental mechanical strain rather than to reproduce real collapse conditions. By, analysing the fiber's response to these mimicked conditions, we can better understand the strain thresholds that could indicate potential structural failures.

During the experiment, an optical power meter was used to monitor power fluctuations of the transmitted light through the fibers. Monitoring was done for a cumulative period of 120 s. The SOP change of the signal propagating through the fiber was recorded by the polarization analyser. To visualize and analyse the data, a computer was utilized. The computer facilitated real-time data acquisition and processing, allowing for detailed analysis of the power fluctuations and assessment of each fiber's sensitivity to the applied strain.

In this experiment, the fiber was clamped using fixed, smooth plastic plates to ensure a uniform and controlled application of compressive force. The smoothness of the plastic surfaces was intended to minimize unintended micro-bending variations caused by surface roughness. However, it is acknowledged that in practical field conditions, surface contact may vary due to rough or uneven mounting surfaces. Variations in surface roughness can significantly influence the degree of micro-bending, and thus optical attenuation, by introducing localized pressure points (Gardner, 1975). While roughness was not a variable in this experiment, future studies should consider systematically investigating its effect to more closely replicate diverse installation scenarios and improve the robustness of sensing system design.

Subsequently, light emanating from three laser sources: Wavelength Division Multiplexing (WDM) tunable laser from Thorlabs (model TLS1550-C), Mach-Zehnder Modulator (MZM) laser from Photline (Modbox platform), and Distributed Feedback (DFB) laser from Thorlabs (model LP1550 – SAD2), each operating at a wavelength of 1550 nm was directed into a G655 OFS fiber type at different times. Each source operated in the 1550 nm region, matching the low-loss window of the G655 OFS fiber (International Telecommunication Union, 2006; OFS, 2023). The key technical specifications of these sources are provided in Table 1. To ensure uniformity in data collection and eliminate potential confounding variables, the input power (0.49 dBm) and operating wavelength (1550 nm) were deliberately held constant across all fiber and laser source configurations. This aimed at investigating the performance of the three laser sources. By evaluating the performance of WDM, MZM, and DFB laser sources, we assessed their effectiveness in detecting and measuring strain under these simulated conditions. This comparative analysis aims to determine the most suitable laser technology for accurate and reliable hazard technology.

Each laser source was selected to explore different sensing conditions. The DFB laser offers cost-effective, narrow-linewidth option for stable sensing; the MZM laser source provides an ultra-low noise and high coherence for detecting minute changes in attenuation; and the WDM laser source enables multi-channel interrogation, paving way for future multiplexed sensor systems. The performance of these sources in combination with the G655 OFS fiber was evaluated in terms of their ability to resolve micro bending-induced attenuation, as described in section 3. Better performance of a laser is largely determined by its linewidth; narrower linewidths correspond to higher coherence and stability, which enhance measurement precision and reduce noise (Agrawal, 2012).

G655 OFS was selected for this study due to its favourable properties

Table 1
Laser source technical specifications.

Parameter	DFB laser (Thorlabs LP1550-SAD2)	MZM laser (Photline Modbox)	WDM laser (TLS1550-C)
Wavelength range	1550.12 nm (fixed)	1525–1565 nm (tunable input)	1530–1570 nm (C-band)
Linewidth	~2 MHz	<100 kHz	~100 MHz
Coherence length	~100 m	>500 m	10–30 m
Output power	+ 3 dBm	+ 5 dBm	0 to +2 dBm (per channel)
Modulation Bandwidth	Up to 10 GHz	Up to 40 GHz	~2 GHz
Relative Intensity Noise	Moderate	Low	Moderate
Polarization	Moderate	Low	Variable (channel dependent)
Output type	CW (narrow linewidth)	CW with high-speed modulation	Multi-channel CW (ITU grid spacing)

for optical strain sensing in harsh environments such as underground mining. Unlike the standard G652 fibers, which exhibit near-zero dispersion at 1310 nm and higher chromatic dispersion at 1550 nm, G655 is engineered to have a non-zero but low dispersion near 1550 nm, reducing nonlinear effects and maintaining signal integrity over long distances (International Telecommunication Union, 2006). This makes it ideal for high-resolution, long-range sensing where minimal pulse broadening and loss are critical. Additionally, G655 fibers typically exhibit lower attenuation (< 0.20 dB/km) at 1550 nm, enhancing signal-to-noise ratio in strain sensing configurations (OFS, 2023). In applications involving micro bending or deformation-induced attenuation, G655′s optimized core profile and mode confinement provide a consistent and sensitive response to applied mechanical strain. Its compatibility with the C-band laser sources and WDM systems makes G655 attractive for scalable, multiplexed sensor networks. These qualities collectively make G655 OFS fiber a practical candidate for experimental validation of fiber optic sensing under simulated mine conditions.

3. Results and discussion

3.1. Mechanism of optical loss due to micro-bending

The primary cause of optical attenuation observed in this study is micro-bending, which arises from small-scale, localized deformations along the fiber axis caused by external mechanical pressure. These micro-bends induce coupling of light from the guided core mode into radiation or cladding modes, resulting in increased optical loss (Gardner, 1975). This effect is especially significant in single-mode fibers, where the core is highly sensitive to such perturbations. The degree of micro-bending loss depends on factors including the fiber's core-cladding structure, coating materials, and the nature of the physical contact surface. In this experiment, smooth plastic plates applying uniform compressive force were utilized.

Random micro-bends, even of slight amplitude, can substantially increase attenuation by promoting mode coupling and scattering within the fiber (Gardner, 1975). Mechanical stresses such as micro-bending can also induce birefringence and polarization mode coupling, affecting the state of polarization and contributing to signal degradation (Rashleigh, 2003). These combined effects underscore the importance of understanding mechanical interactions in fiber optic sensor design and deployment.

3.2. Power and SOP fluctuations

The experiment was conducted to determine the most effective combination of laser source and optical fiber for detecting strain, with conditions mimicking a mine collapse. At first, when light from a 1550 nm DFB laser source was injected to the four fiber types under investigation, the input power before loading was 0.49 dBm, 0.50 dBm, 0.54 dBm and 0.81 dBm, on the G655 OFS, G655 Corning, PMF Corning, and G652 Corning respectively as shown in Fig. 2. The optical power measurements reported in this study were subject to a measurement uncertainty of ± 0.005 dB, based on the resolution of the optical power meter used. This level of precision is sufficient for resolving attenuation changes associated with incremental mechanical strain in the fiber. After 18 kg load was attained, the power readings were 0.01 dBm, 0.04 dBm, 0.08 dBm, and 0.18 dBm on the PMF Corning, G655 OFS, G652 Corning, and G655 Corning respectively. This equated a power loss of 0.32 dB, 0.45 dB, 0.53 dB, and 0.73 dB, on the G655 Corning, G655 OFS, PMF Corning and G652 Corning respectively. A sensitivity of 0.0018 dB/N, 0.0025 dB/N, 0.0029 dB/N, and 0.0041 dB/N was achieved on the G655 Corning, G655 OFS, PMF Corning and G652 Corning respectively.

It is important to note that while the applied load (up to 18 kg) does not represent the extreme or catastrophic stress levels encountered during mining failures, it served as a sufficient and controlled stimulus for evaluating the strain sensitivity of bare fibers. The goal was to investigate whether the optical signal attenuation could reliably reflect mechanically induced changes in the fiber. Future studies will scale the test setup using ruggedized fiber cables and more representative mechanical loading scenarios to improve applicability to real-world mining environments.

Table 2 gives a summary of the SOP changes with corresponding SOP speeds of a signal propagating through different fibers under simulated conditions.

For purposes of investigation, we looked into the fiber response when the masses are unloaded from 18 kg until the fiber is completely free of strain at the same time interval as that used during loading. It is observed in Fig. 3, that when the load is removed power increases up to almost the same initial readings before loading took place. Implying the fiber material has not reached the breaking/deformation point. This is why a maximum of 18 kg was chosen.

In this work, three types of laser sources were evaluated for their effectiveness in fiber optic sensing applications: Distributed Feedback (DFB) laser from Thorlabs company, Wavelength Division Multiplexing (WDM) laser from the Thorlabs company, and Mach-Zehnder Modulator (MZM) laser from Photline company as shown in Fig. 4. Selecting the appropriate laser source is crucial for optimizing the performance of fiber optic sensing systems. All laser sources operated at a wavelength of 1550 nm, ensuring uniformity in measurements. Light emanating from each of the three laser sources was directed into the G655 OFS fiber so as to evaluate the strain measurement performance of each. This study used G655 OFS fiber, a non-zero dispersion-shifted (NZDS) single-mode fiber (SMF) designed to minimize dispersion and nonlinearities near 1550 nm window. This makes it particularly suitable for high-performance optical sensing where attenuation and phase changes are used to infer mechanical strain. The G655 OFS fiber was considered because it is optimized for reduced dispersion, making it suitable for long-distance transmission hence a greater coverage of the mine.

The power reading before the fiber was subjected to loads was 0.49 dBm for the three laser sources. The input power was maintained at approximately 0.49 dBm for all three laser sources throughout the experiment to ensure a stable baseline for comparison. After the 18 kg load, the power recorded on the optical power meter was 0.04 dBm for the DFB and WDM respectively, while the power readings on the MZM was 0.06 dBm. A power loss of 0.45 dB was achieved on the DFB and WDM sources, 0.43 dB on the MZM source. This translated to a sensitivity performance of 0.0025 dB/N for the DFB and WDM sources, 0.0024 dB/N for the MZM source.

The three laser sources, all operating at a wavelength of 1550 nm, demonstrated overall consistency in performance and signal stability. Although all were capable of accurate strain measurement, there were very minimal differences in their performance. For strain measurement under severe conditions such as a mine collapse, MZM lasers would generally be the best choice due to their high sensitivity and ability to detect small changes in strain. The optimal combination for strain measurement was identified as the pairing of the MZM laser source with the G655 OFS fiber. This combination offered the best performance, providing reliable signals with minimal attenuation and accurate detection of power fluctuations under applied strain.

This system was then configured such that beyond a certain set power threshold an alarm is raised. From Fig. 4. a program was

Table 2
SOP changes and SOP speeds of different fibers loaded with 18 kg mass.

Fiber type	Maximum SOP $\pm$ 0.5 change (in degrees (^{0}))	SOP speeds $\pm$ 0.0005 (^{0}/s)
G652 Corning	565	4.708
G655 Corning	330	2.750
G655 OFS	615	5.125
PMF Corning	443	3.692

developed for purpose of automation such that when power fluctuates beyond 0.2 dBm then an alarm is switched on. This will then alert the miners of a potential collapse enhancing their safety. The 0.2 dB threshold was selected based on observed attenuation ranges that reliably indicate applied strain. In practice, this threshold can be adjusted depending on baseline fiber loss and installation conditions.

3.3. Limitations and real-world applicability

While the findings from this study offer a foundational understanding of fiber response under strain, certain limitations exist regarding their applicability in real mining conditions. The experiments were conducted using bare fibers in a controlled lab setting with uniform loading and minimal environmental variability. In real-world deployments, factors such as fiber jacketing, installation-induced bending, temperature fluctuations, and mechanical abrasion may influence sensor performance. Future studies will extend this work by testing ruggedized fiber cables in field-mimicking environments to validate operational robustness.

In addition to mechanical strain, practical mine environments present other variables such as temperature fluctuations, and humidity. While our current study focused on strain as the primary hazard indicator, it is important to note that optical fiber sensors—particularly those operating at 1550 nm—are inherently immune to EMI due to their dielectric nature, making them well suited for deployment in electromagnetically noisy environments such as underground mines. Regarding thermal sensitivity, silica-based optical fibers exhibit minimal thermal cross-sensitivity in strain measurement configurations, especially when short lengths are used and the wavelength is kept stable. The temperature-induced variations in signal are significantly smaller than those caused by strain-related micro-bending, and are thus negligible within the controlled conditions of this study. Nonetheless, future studies will include extended testing under varying temperature and humidity conditions to quantify cross-sensitivity effects and enhance system robustness for field deployment.

4. Conclusion

A strain sensitivity of 0.0024 dB/N was achieved using the MZM-G655 OFS fiber combination, which demonstrated superior stability, sensitivity, and accuracy. This makes it the optimal laser-fiber pairing for precise strain measurements in mining applications. The experimental setup, involving different optical fibers and laser sources, showed that the chosen MZM laser source and G655 OFS fiber not only provided reliable measurements under controlled strain but also maintained consistent power outputs when tested with different laser sources (DFB, MZM, and WDM) in Fig. 4. This consistency in power levels confirms the robustness of this combination, even when the applied loads varied.

It's important to note that the values presented for input power in Fig. 2 (approximately 0.8 dBm) before loading, and the similar values after unloading (Fig. 3), reflect the real-world behaviour of fiber sensors under strain. In contrast, the 0.49 dBm input power in Fig. 4 was deliberately maintained across all laser sources to ensure a controlled comparative evaluation of the lasers' performance in detecting strain, which accounts for the slightly different figures in the power readings.

The findings highlight the capability of this optimized system to serve as a reliable monitoring tool for early hazard detection in mine environments, where accurate and continuous strain measurement is critical for safety.

CRediT authorship contribution statement

W.K. Nyarangi: Writing – original draft. **E.K. Rotich Kipnoo:** Supervision, Conceptualization. **F.W. Masinde:** Supervision, Conceptualization. **D.W. Waswa:** Resources, Investigation, Funding acquisition. **J. Jena:** Resources, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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