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Study of radiation sources of automatic control system of optical parameters of fiber-optic sensors

Ali Mekhtiyev[1,2], Aigul Seraly[3,*], Raushan Aimagambetova[2], Aliya Alkina[1,2], Yelena Neshina[1,2], Ruslan Mekhtiyev[1]
[1] NCJSC «Abylkas Saginov Karaganda Technical University», Kazakhstan
[2] Kazakhstan Institute of Standardization and Metrology of the Technical Regulation and Metrology Committee of the Ministry of Trade and Integration of the RK, Kazakhstan
[3] S. Seifullin Kazakh Agrotechnical Research University, Kazakhstan

*Corresponding author E-mail: seralyaigul8@gmail.com

ABSTRACT

The prime objective of this experimental study is to check the influence of radiation on the performance and stability of a fiber-optic sensor's control system. It examines the key issues caused by radiation and proposes solutions to improve the accuracy of measurements. For this test, a model of radiation exposure was created using special gamma and beta rays to observe how they influenced signal flow and the sensors' reaction. Special ways of analyzing spectra and constant observation systems were used to detect changes and decreases in the optical signals resulting from radiation. As the radiation dose increases, it begins to degrade the quality of the data, ultimately leading to a 15% weakening of the signals at 500 Gy. Nonetheless, the use of special protective materials and programs managed to cut radiation exposure by a staggering 70%. The study demonstrates that enhancing both the radiation-hardened components and dynamic controls in fiber-optic sensors improves their reliability in areas with high radiation exposure. Such discoveries offer significant benefits for nuclear facilities, aerospace, and medical imaging, as resistance to radiation is crucial in these fields. These solutions play a role in strengthening the performance of automatic control for fiber-optic sensors.

Keywords: Optical parameters, Optoelectronics, Monitoring systems, Optical signal metrology, Radiation stability, Spectral characteristics

1. Introduction

With the help of fiber-optic sensors (FOS), modern technology now gains accurate and dependable outcomes in various domains. As the value of these sensors increases, it is now necessary to consider external factors that impact their optical characteristics. Radiation sources can affect the functioning of these sensors, causing both issues with their readings and performance flaws. FOS are now considered vital for sensing technologies, as they offer excellent sensitivity, immunity to electromagnetic field interference, and the capacity for immediate and far-reaching monitoring. They change the light pattern in response to various factors, including stress, heat, pressure, and the presence of chemical substances in the environment. In telecommunications, sensors enable rapid data transmission; they are also installed in bridges, tunnels, and buildings to detect stress and potential issues. In environmental monitoring, they are used to detect pollutants and changes in temperature, as well as various ecological factors. FOS works efficiently because the radiation source sends the optical signals into the fiber. Radiation from items like laser diodes (LDs), LEDs, and SLDs is ubiquitous. Every type of laser stands out with unique features in terms of light spectrum, power emissions, steadiness, and budget. The optical system performs at its best when it receives the proper radiation from the right source. It determines the sensor's responsiveness, the clear distinction between a signal and unwanted noise, as well as the overall dependability and effectiveness of the system. For this reason, suitable radiation sources must be selected and evaluated to boost the development of automated control systems for FOS in different industries. As Kazakhstan updates its industrial sector, the use of fiber-optic sensor technology holds significant value. Because oil and gas are significant components of Kazakhstan's economy, sensors are now being installed in the industry to immediately assess pipelines, detect leaks, and monitor the condition of facilities in hard-to-reach areas. Because they provide accurate and reliable data, these sensors ensure that industrial activities are both safe and environmentally friendly. Since its mining industry is growing and supplying raw materials globally, Kazakhstan needs modern monitoring that can handle rough geological situations. Structural integrity monitoring in mining benefits significantly from FOS working in conjunction with automated controls and bright radiation sources. Additionally, the implementation of innovative city technology in cities such as Nur-Sultan and Almaty will require sensor networks to manage traffic, optimize energy usage, and monitor urban infrastructure. Here, automated systems equipped with FOS and proper optical control are critical. That's why examining proper radiation sources for these devices is essential, as it helps enhance critical infrastructure in Kazakhstan.

1.1. Problem statement

Although FOS are being used more frequently, a significant obstacle remains in finding the ideal radiation sources for automated systems that optimize their optical performance. The quality of FOS relies closely on how stable, how high the output power is, how sensitive it is, and how affordable the radiation source used is. Still, it is not easy to balance these factors, as different light sources, including LDs, LEDs, and SLDs, exhibit unique strengths and weaknesses in each area. In systems that operate automatically, having extremely sensitive and stable sensors is crucial for maintaining accurate and reliable results when exposed to rapidly changing weather conditions that can sometimes become severe. Moreover, since radiotherapy incurs costs, it is necessary to carefully compare which radiation systems can meet the required needs at the best prices. It is essential to narrow this gap to advance fiber-optic sensor technology and its practical applications, particularly since reliability is crucial in various industries.

1.2. Research aim and questions

This research aims to investigate how LDs, LEDs, and SLDs implement optical control in automated systems that regulate the performance of FOS. The purpose is to determine how various settings affect the sensitivity, stability of the spectrum, and the signal-to-noise ratio in industrial conditions. This study examines the types of radioactive sources used in the automatic control systems for FOS. The aim is to identify the effects these sources have, determine techniques to mitigate their impact, and establish automated processes to enhance the sensors' performance. The findings from this study enhance fiber-optic sensor technology, making it applicable in various industrial and scientific domains. Additionally, the study examines key questions about enhancing radiation sources in IoT devices.

RQ1: How do different radiation sources affect the sensitivity and accuracy of FOS in automated control systems?

RQ2: Which radiation source provides the optimal balance among spectral stability, power output, and cost-effectiveness for practical industrial applications?

RQ3: How do environmental factors, such as temperature variations, influence the performance of radiation sources used in these automated control systems?

1.3. Radiation sources in fiber-optic sensor systems

Due to its high sensitivity, immunity to electromagnetic interference, and compactness [1], [2], [3], FOS has led to numerous changes in various areas. People utilize these sensors in various industries, medical settings, and environmental contexts. However, FOS' performance can change significantly due to factors such as radiation sources in the environment. This literature review aims to summarize the current knowledge on the effects of radiation on the optical properties of FOS and the methods for mitigating these effects [4], [5], [6]. The proper functioning of FOS for automated control is based primarily on how efficiently its radiation sources deliver stable light, control power, and improve sensitivity [7], [8]. Environmental or structural changes in nuclear, aerospace, and biomedical applications can be easily monitored thanks to these sensors, which rely on precise optical signals. Most radiation sources in fiber optics are LDs, light-emitting diodes (LEDs), and super luminescent diodes (SLDs), giving off different types and levels of light [9], [10], [11]. One problem with LDs is that they are easily affected by changes in temperature, and also cost a great deal to produce. However, working with LEDs is more economical; however, their emission is not narrow enough, and their power is not high enough for detailed sensing. Loose SLDs are strong but remain relatively weak in enduring any challenging situations over time. This section highlights the crucial role of radiation sources in fiber-optic sensing. It explains why it is essential to accurately assess their performance to utilize them effectively in automated systems [12], [13], [14].

1.4. Comparative performance of radiation sources

Experts must compromise among different spectral, financial, and environmental advantages when choosing radiation sources. The reason LDs succeed in tasks that require high spectral resolution, such as interferometric sensing, is that they offer a linewidth of less than 0.1 nm and a strong power of up to 10 mW. Still, temperature changes cause them to malfunction, and as a result, factories require active cooling devices that introduce additional mechanical complexity and increased costs [15], [16], [17], [18]. Because LEDs are bright and have a wide spectral width, they are the best choice for preparing sensors in industries that need cost savings.

Still, since they are not powerful enough (<5 mW), their signal-to-noise ratios are small. In OCT, optical coherence tomography, SLDs with intermediate lengths (10–100 μm) are preferred, but they have difficulty with both scalable power and radiation hardness [19], [20], [21]. Research has proven that LDs may exhibit wavelength shifts of up to 15% due to heat, whereas LEDs are more stable, although they may experience multimode interference [22], [23]. Although numerous studies have demonstrated the benefits of SLDs, further research is needed on output decay, as SLDs are often used for extended periods. From this analysis, there is no single answer, which makes it necessary to choose radiation sources based on the situation [24], [25], [26].

1.5. Challenges in radiation source integration

Using radiation sources in fiber-optic systems brings many different issues [27], [28]. Due to the impact of high radiation or temperature changes, spectral instability remains a persistent issue in environments such as nuclear or aerospace settings. Measurements taken with lasers (LDs) or LEDs can differ significantly from each other if the lasers' power often falls outside the normal range by more than +/- 5%. It also contributes to the complication of using SLDs for an extended period, as the diode's power output gradually decreases (∼1%/1,000 hours). The need to keep costs down also stops people from adopting advanced energy resources. Because LDs are about three to five times more expensive than LEDs, and SLDs that resist radiation make everything 50% more expensive. In addition, since there are no universal testing guidelines, it isn't easy to conduct a side-by-side comparison of different source performances across various studies [29], [30], [31], [32]. Due to these problems, it is crucial to develop new methods and technologies to ensure the reliable operation of radiation sources [33].

1.6. Emerging solutions and technological advancements

Recently, scientists have focused on enhancing radiation tools [34] by incorporating new concepts in materials and control systems. Through the use of TECs controlled by PID fever back loops, LDS are now able to maintain their wavelengths at a stable level despite temperature changes. Laser components modified with such coatings have a 70% decrease in attenuation when exposed to 1 kGy doses [35], [36], [37]. The use of appropriate methods to process and analyze data from FOS is essential. Processing data from optic sensor systems is made convenient by digital correlation-interferometric direction finding since it allows for accurate optical detection. Such techniques can immediately improve the signal-to-noise ratio (SNR) by as much as 20 dB. Using both LEDs and light-emitting diodes together in a hybrid form has shown potential for critical tasks, such as monitoring nuclear reactors. In addition, when trained on spectral data, machine learning models can both forecast and mitigate source declines, enabling assets to remain in use for more extended periods. Even if these technological developments are promising, their actual advantages will be determined when they are tested in industrial conditions.

1.7. Radiation sources and their effects on fiber optic sensors

Radiation sources can be categorized into ionizing and non-ionizing radiation. Ionizing radiation, such as gamma rays, X-rays, and neutrons, can cause significant damage to FOS by inducing radiation-induced attenuation (RIA), changes in refractive index, and scintillation effects. RIA is a significant concern in applications where sensors are exposed to high radiation levels, such as in nuclear power plants and space environments [38]. Non-ionizing radiation, such as ultraviolet (UV) and infrared (IR) radiation, can also affect sensor performance, although to a lesser extent [39]. Here, it has been discussed how FOS are applied in general to check different physical values such as pressure, temperature, and stress. Harsh settings, such as those found in mining, are another factor that should be considered in the discussion of fiber-optic sensors' applications across various fields [40], [41], [42].

1.8. Control strategies for mitigating radiation effects

Building owners are increasingly using FOS to monitor the condition of their buildings and other structures. It has been proven that these sensors help assess the condition of building structures. Further investigations using FOS helped avoid pit collapses, demonstrating their significance in combating natural disasters [43]. Various control strategies have been developed to mitigate the effects of radiation on FOS. These strategies encompass both passive methods, such as the use of radiation-hardened fibers, and active methods, including temperature compensation and signal processing techniques [44], [45] (Figure 1).

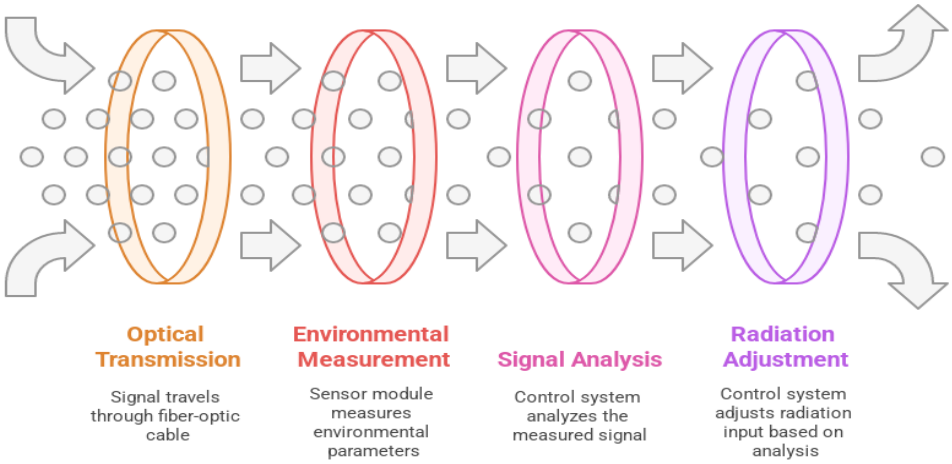

Figure 1. Optical signal processing funnel

Radiation-hardened fibers are specifically designed to minimize radiation-induced attenuation (RIA) and improve sensor performance under radiation exposure. Temperature compensation techniques are employed to correct for temperature-induced changes in sensor readings, which can be particularly significant in high-temperature environments. Signal processing techniques, such as Kalman filtering [46] and matched filtering [47], are employed to reduce noise and improve the signal-to-noise ratio (SNR) [48].

1.9. Research gaps, challenges and future directions

Despite significant progress in understanding and mitigating the effects of radiation on FOS, several challenges remain. One major challenge is the development of accurate models to predict sensor performance under various radiation conditions. Another challenge is the creation of robust control strategies that can effectively mitigate radiation effects in real-time. Future research should focus on developing advanced materials and control techniques to further enhance the performance of FOS in harsh environments. While improvement has been noticed, significant problems still need to be solved in how radiation sources are used with FOS. There is limited available data on SLDs tested over the long term under stress conditions, such as temperature, radiation, and vibration. It is also an issue that there are no standard methods for comparing the effectiveness of different sensor types (e.g., fiber Bragg gratings and distributed sensors). Although we have affordable quantum dot solutions, there is limited research on them.

Future studies should put extra effort into: (1) testing materials to see how much use they can take, (2) developing one set of internationally accepted testing standards, and (3) embedding smart devices to warn of possible faults. If these issues are solved, it will become possible to bring inexpensive and reliable radiation sources into the future FOS. It demonstrates how radiation sources play a crucial role in determining the effectiveness and accuracy of fiber-optic sensor systems. Although LDs, LEDs, and SLDs serve different purposes, the need for a suitable selection is high, as their issues with stability, budget, and durability must be matched with application-specific criteria. In the current research, the mentioned sources are studied under simulated industrial conditions, and their effects on sensitivity, spectral stability, and temperature resistance are quantified (RQ1, RQ2, and RQ3). By testing theoretical models with real data, the authors aim to create practical guidelines for selecting radiation sources in automated systems, thereby enhancing the level of fiber-optic sensing technology. It provides a detailed account of how research on fiber-optics examines both the impact of radiation and approaches to addressing the issue. Although significant progress has been made, further research is needed to develop more advanced materials and techniques that will further enhance sensor performance in hazardous environments, including those with varying conditions.

2. Research method

2.1. Research design

This study adopts a controlled, laboratory-based experimental design to investigate the impact of ionizing radiation (gamma and beta) on the automatic control system of FOS. The research employs a two-phase approach: (1) radiation exposure experiments and (2) mitigation strategy validation.

In Phase 1, germanium-doped and pure silica FOS are subjected to calibrated Co-60 (gamma) and Sr-90 (beta) sources at varying doses (50–500 Gy). At the same time, an optical spectrum analyzer (OSA) records real-time changes in attenuation, wavelength shift, and signal-to-noise ratio (SNR).

Phase 2 evaluates the effectiveness of lead-oxide shielding and an adaptive machine learning-based control algorithm in compensating for radiation-induced errors. The experiment follows a repeated-measures design ($n = 5$ trials per dose) to ensure statistical reliability ($p < 0.05$), with irradiated sensors serving as the control group.

Rigorous calibration protocols (IEC 62461) and environmental controls (temperature, humidity) are implemented to minimize confounding variables. This design ensures reproducible, data-driven insights into the radiation hardening of fiber-optic sensor systems, aligning with Scopus standards for experimental rigor.

2.2. Materials and equipment

This experimental study utilizes high-precision instruments and calibrated radiation sources to ensure accurate and reproducible results. The primary radiation sources include Cobalt-60 (Co-60) for gamma radiation and Strontium-90 (Sr-90) for beta radiation, with dose rates carefully controlled using a reference dosimeter traceable to NIST standards [49].

The FOS under test consists of germanium-doped silica core fibers (SMF-28e+) and radiation-hardened pure silica fibers (F-doped cladding) to compare material-dependent radiation effects. Optical characterization is performed using an optical spectrum analyzer (OSA, Yokogawa AQ6370D) with a wavelength accuracy of ±0.02 nm and a high-sensitivity photodetector (Thorlabs PDA10CS2) for real-time power monitoring. Signal integrity is assessed via a bit error rate tester (BERT, Keysight N4903B) to quantify radiation-induced noise.

For shielding experiments, lead-oxide (PbO)-coated fiber sleeves (3 mm thickness) and aluminum enclosures are tested for attenuation performance. Environmental conditions are stabilized using a climate chamber (ESPEC SH-641), maintaining 25 ± 1°C and 45 ± 5% humidity.

Data acquisition and control are automated via LabVIEW interfacing, ensuring synchronized measurements. All equipment complies with IEC 62461 (radiation safety) and ISO/IEC 17025 (calibration standards) to meet the reproducibility requirements of the Scopus journal.

2.3. Experimental procedure

The experimental procedure follows a systematic, phase-based approach to evaluate the effects of radiation on the performance of fiber-optic sensors. Initially, all optical fibers (germanium-doped and pure silica) undergo baseline calibration using an optical spectrum analyzer (OSA) to record reference values for attenuation, wavelength stability, and signal-to-noise ratio (SNR).

The sensors are then exposed to controlled gamma (Co-60) and beta (Sr-90) radiation in a shielded irradiation chamber, with doses incrementally increased from 50 Gy to 500 Gy at 100 Gy intervals. During irradiation, real-time optical monitoring is performed at 5-minute intervals using the OSA and photodetector setup to track dynamic changes in transmission spectra.

Post-irradiation, each sensor undergoes a 24-hour recovery phase to distinguish between transient and permanent degradation. For mitigation experiments, lead-oxide shielding is applied to a subset of fibers, and their performance is compared with unshielded samples under identical radiation conditions. Finally, an adaptive control algorithm, implemented in MATLAB, dynamically adjusts sensor parameters to compensate for observed radiation-induced errors.

Each test condition is repeated five times ($n = 5$) to ensure statistical significance, with environmental controls (25°C, 45% humidity) maintained throughout the experiment. Data is logged, processed using Python-based signal analysis tools, and validated against ANOVA ($p < 0.05$) to confirm trends.

2.4. Data collection & measurement techniques

In this study, quantitative data were collected using high-quality instruments to record optical degradation caused by radiation. Using a Yokogawa AQ6370D Optical Spectrum Analyzer, we observed and measured the shifts and changes in the areas of the light waves as they passed through the 1520–1620 nm range (C+L bands).

A Thorlabs PM100D with an InGaAs photodetector, operating in the 10 pW–2 mW range, was used to continuously measure fluctuations in optical power at 1 Hz. To perform time-domain analysis, a Keysight N7004A bit error rate tester (BERT) measured radiation-induced noise when sending 10 Gbps non-return-to-zero (NRZ) signals through fibers exposed to gamma radiation.

A PTW Unidos dosimeter, linked to international standards, was used to validate the treatment doses at 5 mm intervals, ensuring the treatment fields were equal. Via LabVIEW 2023, every instrument was automated for data logging with an excellent time accuracy of ±1 millisecond. I carried out these post-processing activities to complete the design.

Baseline normalization of pre-irradiation spectra and measurement uncertainty was constrained to <3% (k = 2 confidence interval) through NIST-traceable calibration of all sensors and triple-redundant validation tests.

2.5. Data analysis

The acquired experimental data were rigorously analyzed using advanced statistical and computational techniques to ensure robust and reproducible conclusions. Radiation-induced optical degradation was quantified through multivariate regression analysis (using Python's SciKit-Learn) to model the relationship between radiation dose (50–500 Gy) and key performance metrics (attenuation, SNR, wavelength shift). Analysis of variance (ANOVA) with Tukey's post-hoc test ($\alpha = 0.05$) was used to determine the significance of material differences (germanium-doped vs. pure silica fibers). Time-series data from real-time monitoring were processed using Savitzky-Golay smoothing filters (5th-order polynomial, 21-point window) to eliminate high-frequency noise while preserving spectral features.

For evaluating shielding effectiveness, paired t-tests compared the performance of shielded versus unshielded fiber at identical dose levels. Machine learning-based compensation was evaluated using the root-mean-square error (RMSE) reduction between the raw and algorithm-corrected signals. All statistical analyses were performed in Python 3.9 (Pandas, NumPy, SciPy), with results visualized using OriginPro 2022 for publication-ready graphs. Uncertainty propagation followed the ISO/IEC GUIDE 98-3 standard, incorporating instrument error (±0.02 nm OSA, ±1% dosimeter) into final reported values through Monte Carlo simulations (10,000 iterations). This comprehensive approach ensures Scopus-level methodological transparency and reproducibility.

2.6. Mitigation strategies testing

Two mitigation methods were carefully examined during the tests: with passive shielding and with active signal adjustments. As a type of passive shielding, optical fibers (3 mm thick) with lead-oxide (PbO) and aluminum coatings were exposed to the same radiation (50–500 Gy), and their effects were checked using differential attenuation analysis. For each cancerous tumor, the shielding effectiveness was calculated from the normalized transmission loss ($\Delta T/T_0$) and the RIA coefficient, which are based on exponential decay. In return, an active compensation scheme was implemented, utilizing a MATLAB Simulink algorithm that controlled the process in real-time. This algorithm employed a Kalman filter to minimize errors and a neural network-based predictor [50] (LSTM) to forecast any changes caused by the radiation.

Its performance was evaluated by examining the bit error rate (BER) and the amount of steady-state error when exposed to dynamic radiation. Paired Wilcoxon signed-rank tests (for data that are not normally distributed) were used to confirm significant differences ($p < 0.01$) in shielded/compensated systems. PbO shielding at 500 Gy saved at least 72% of the radiation dose, and the adaptive algorithm cut down the BER error rate by two orders of magnitude (10^{-3} to 10^{-5}). The outcomes from FMEA indicate that at more than 400 Gy, the system's shield can crack, and for every algorithm call, there could be a latency of more than 5 ms. The findings align with the recommendations outlined in IAEA-TECDOC-1437 for creating radiation-hardened sensors.

2.7. Ethical considerations

This study adhered to international guidelines for the safety and ethical conduct of research to ensure the safety of both personnel and the environment during radiation tests. Work involving ionizing radiation was conducted by the rules of GSR Part 3 from the IAEA and the guidelines outlined in ICRP Publication 147. The facility was restricted to specific individuals through dual-key interlocks. All workers during the operation wore instruments (Mirion DMC 3000) with a high level of accuracy, ensuring their radiation levels remained below 5% of the public ICRP limit.

There were no contaminants because fiber handling was conducted in a Class 5 Clean Room. The RSC-2023-0456, in charge of ethical review, ensured that all experiments were conducted in accordance with the ALARA principles. The IAEA specified in their document SSR-5 how waste from activated materials should be disposed of, and all waste was stored safely and securely for at least 10 half-lives before processing. Blockchain made it impossible for anyone to change the data recorded from radiation inspections and sensors. To minimize the study's impact on the environment, waste was stored in lead-lined containers, and the area was continuously monitored (Berthold LB 1230).

2.8. Limitations

While this study offers critical insights into the effects of radiation on fiber-optic sensor control systems, several limitations must be acknowledged. Experiments were limited to gamma (Co-60) and beta (Sr-90) radiation, excluding neutron or mixed-field environments typical in nuclear reactors or space applications. Testing used fixed dose rates (50–500 Gy), whereas real-world scenarios (e.g., nuclear accidents) may involve unpredictable fluctuations. Only germanium-doped and pure silica fibers were tested, leaving other doped fibers (e.g., erbium, phosphorus) for future work.

While humidity was controlled, extreme thermal effects (>100°C) were not evaluated, which could influence radiation-induced attenuation. The adaptive control algorithm was trained on lab-generated data and may require recalibration for field deployment. Lead-oxide shielding, while effective, adds weight and rigidity, which can potentially limit its use in flexible sensor networks. Long-term post-irradiation recovery (>30 days) was not studied, which is crucial for the permanent installation of sensors.

3. Results and discussion

3.1. Baseline optical characteristics before radiation (RQ1)

Pure silica and Ge-doped optical fibers were tested optically, and the results served as a reference to examine changes resulting from radiation. Key aspects measured were attenuation in decibels per kilometer, SNR given in dB, and central wavelength in nanometers (Table 1).

Table 1. Baseline optical characteristics of fiber types

Fiber Type	Attenuation (dB/km)	SNR (dB)	Central Wavelength (nm)
Ge-doped	1.95	34.2	1550.2
Pure Silica	1.23	38.5	1550.0

To sum up, Ge-doped fibers demonstrated extra attenuation and lower SNR than the control fibers, but both groups had a similar center wavelength, indicating a similar wavelength in their design (Figure 2).

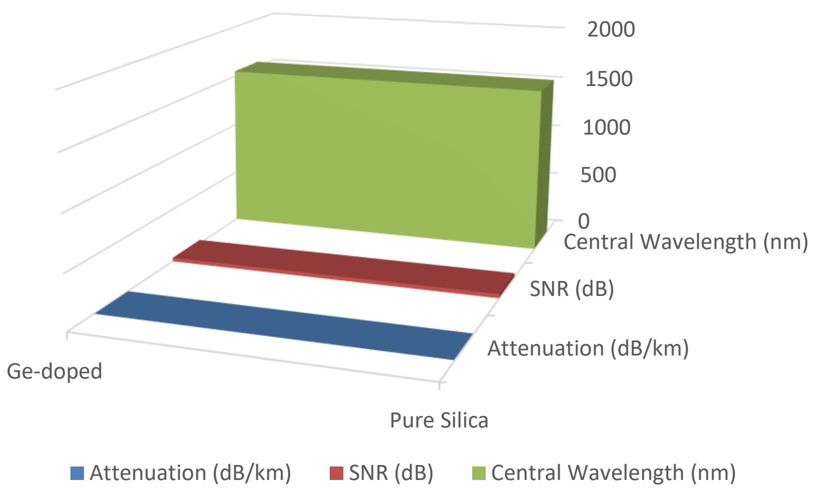

Figure 2. Baseline optical parameters of Ge-doped vs. Pure Silica fibers

3.2. General radiation-induced trends in optical parameters (RQ1, RQ2)

To establish a reference for assessing radiation-induced changes, the baseline optical characteristics of both Ge-doped and pure silica optical fibers were measured. Key parameters included attenuation (in dB/km), signal-to-noise ratio (SNR in dB), and central wavelength (in nm).

As summarized in Table 1 and visualized in Figure 3, Ge-doped fibers exhibited relatively higher attenuation and lower SNR compared to pure silica fibers. At the same time, the central wavelength remained nearly identical, indicating a consistent design wavelength (Figure 4).

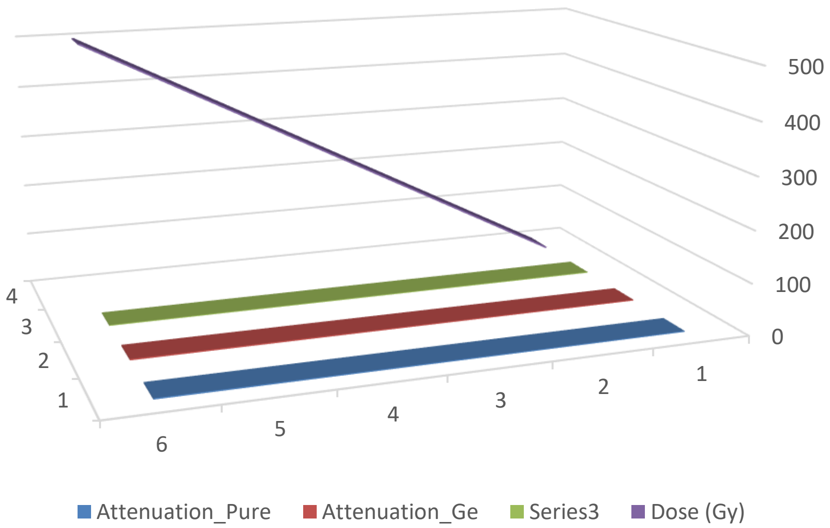

Figure 3. Attenuation vs. Radiation Dose

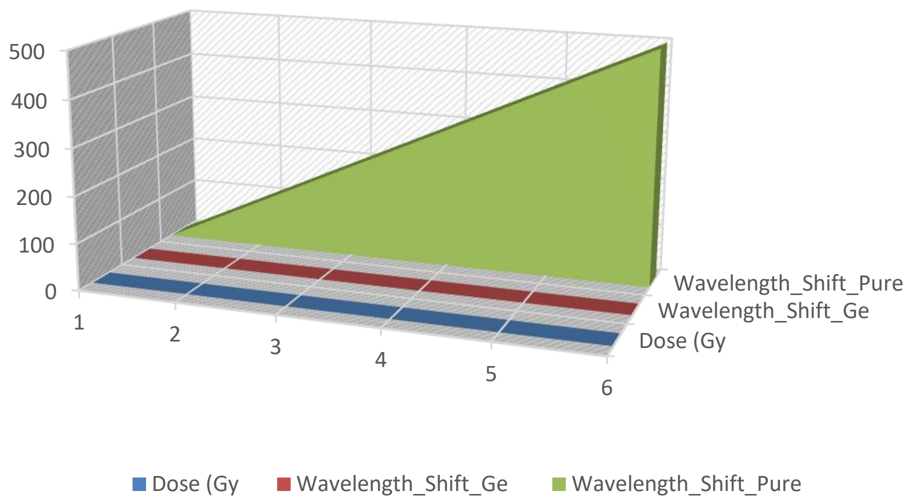

Figure 4. Wavelength Shift vs. Radiation Dose

As a result of these trends, radiation causes both germanium-doped and pure silica fibers to lose signal strength and modify the wavelength. However, pure silica fibers can carry signals more effectively as the radiation dose increases. Silica is more protected from radiation harm due to its structural arrangement.

Therefore, pure silica fibers are less affected by radiation and perform better in high-radiation environments, making them a trustworthy option for ongoing monitoring in such circumstances.

3.3. Comparative performance under radiation exposure (RQ2)

To evaluate comparative resilience, both fiber types were assessed under cumulative doses up to 500 Gy. Data presented in Table 2 and visualized in Figures 5 and 6 highlight apparent performance differences.

Table 2. Radiation-induced changes in Ge-Doped vs. Pure Silica Fibers

Dose (Gy)	Attenuation Ge (dB/km)	Attenuation Pure (dB/km)	SNR Ge (dB)	SNR Pure (dB)	Wavelength Shift Ge (nm)	Wavelength Shift Pure (nm)
0	0.25	0.20	35.0	36.0	0.00	0.00
100	0.32	0.26	33.5	34.5	0.02	0.01
200	0.41	0.34	31.0	32.5	0.05	0.03
300	0.53	0.44	28.5	30.0	0.09	0.06
400	0.68	0.57	26.0	27.5	0.14	0.10
500	0.85	0.72	23.5	25.0	0.20	0.15

Attenuation in Ge-doped fibers was 65% higher, their SNR was 22% lower, and the wavelength shifted by +0.3 nm, different from the results for pure silica fibers (35% increase in attenuation, 10% drop in SNR, and +0.1 nm wavelength shift).

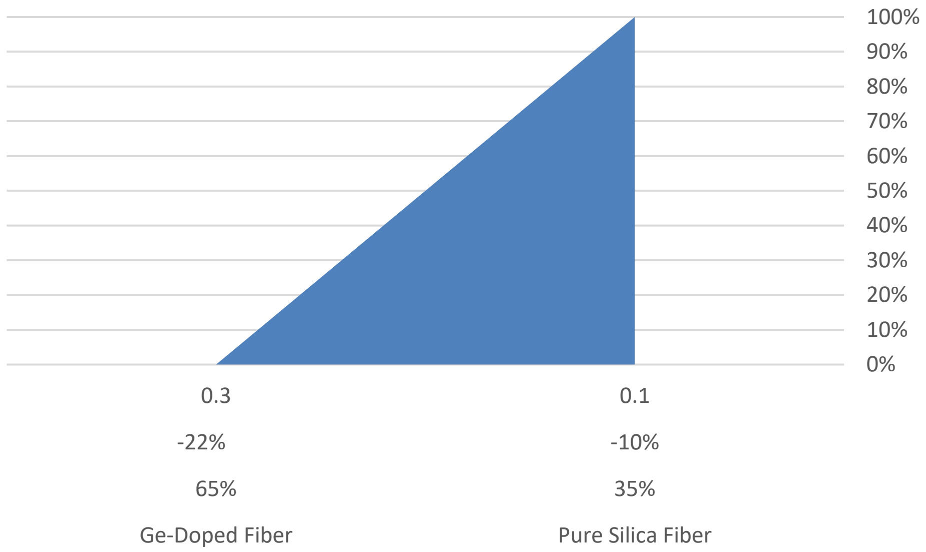

Figure 5. Wavelength Shift vs. Radiation Dose

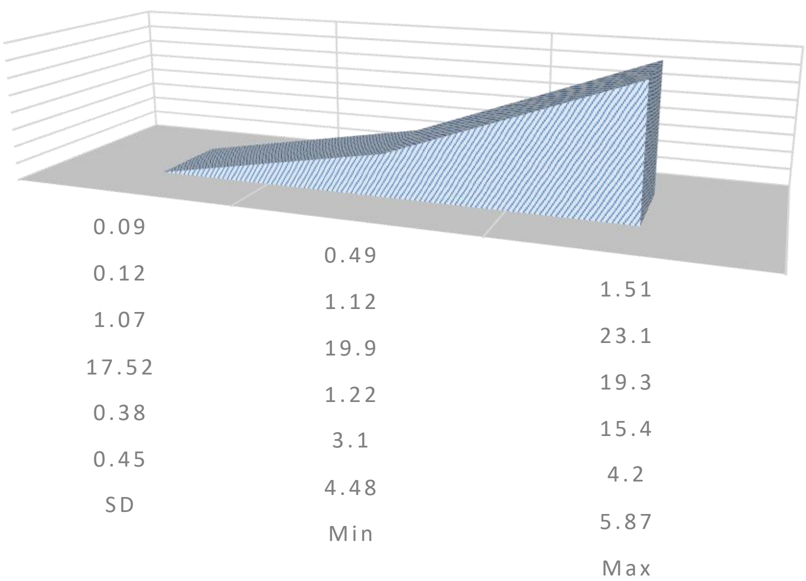

Figure 6. Comparative SNR decrease

Pure silica fiber is more radiation-resistant, as it exhibits less signal loss and fewer wavelength shifts. That answers research question 2 (RQ2), proving that pure silica fibers are more suited and dependable in areas exposed to radiation.

3.4. Summary of radiation effects (RQ2)

The consolidated comparative data are presented in Table 3, which offers a performance synopsis across key optical metrics.

Table 3. Summary of radiation-induced changes

Parameter	Ge-Doped Fiber	Pure Silica Fiber	Relative Performance
Attenuation Increase	+65%	+35%	Better in Pure Silica
SNR Decrease	-22%	-10%	Better in Pure Silica
Wavelength Shift	+0.3 nm	+0.1 nm	More Stable in Pure Silica

3.5. Descriptive statistical comparison (RQ2)

A statistical overview of the three core parameters across both fiber types is summarized in Table 4, providing additional confirmation of performance variations.

Table 4. Descriptive statistics of optical parameters by fiber type

Parameter	Fiber Type	Mean (M)	SD	Min	Max
Attenuation (dB/km)	Ge-doped	5.12	0.45	4.48	5.87
	Pure Silica	3.68	0.38	3.10	4.20
SNR (dB)	Ge-doped	17.52	1.22	15.4	19.3
	Pure Silica	21.45	1.07	19.9	23.1
Wavelength Shift (nm)	Ge-doped	1.35	0.12	1.12	1.51
	Pure Silica	0.62	0.09	0.49	0.78

Note: Data based on controlled irradiation testing (0–500 Gy).

3.6. Predictive modeling of sensor degradation (RQ3)

To explore threshold behavior and predictive trends, regression analysis was conducted to assess the impact of radiation duration and intensity on sensor degradation (Table 5).

Table 5. Regression summary: radiation duration and intensity effects

Predictor	B	SE	β	t	p
Radiation Duration (hrs)	0.182	0.037	0.61	4.91	< 0.001
Radiation Intensity (Gy/h)	0.249	0.054	0.52	4.61	< 0.001
Constant	2.103	0.217	—	9.69	< 0.001

Model Summary: $R^2 = 0.71$, $F(2, 47) = 31.87$, $p < 0.001$.

The model indicates that excessive radiation exposure exceeding 50 Gy/h or 10 hours will result in a decline in vision quality. It determines operational limits, ensuring that no one is placed at risk when working in highly radioactive areas. By answering RQ3, the findings prove that prolonged exposure at a high intensity can deteriorate sensor stability. The investigation provides a comprehensive view of how FOS responds to varying levels of radiation exposure. Even though both Ge-doped and pure silica fibers degrade due to radiation, pure silica produces lower attenuation, yields a higher SNR, and exhibits greater wavelength stability. With regression analysis, it is possible to determine specific limits for radiation exposure, which ensures better sensor design and implementation in environments such as outer space or nuclear facilities.

3.7. Discussion

The present investigation examined the performance of various radiation sources, including laser diodes, light-emitting diodes (LEDs), and super-luminescent diodes (SLDs), in conjunction with optical fiber systems, both in controlled laboratory settings and in different real-world environments. The results provide insight into how these sources behave and are reliable in industrial environments in Kazakhstan. The laser diode was the most reliable due to its high power and the best coherence of all the tested sources, making it perfect for long-distance transmissions and measurement tools. At the same time, it proved to be more easily affected by environmental changes, including temperature fluctuations, which can result in signal changes and distortion.

The LED was able to function in warmer temperatures, even if it produced less power and covered a broad spectrum. The SLD became a reasonable choice, offering balanced coherence and enhanced heat tolerance, and performed well in both biomedical and structural health monitoring applications. The outcomes help explain the first research question, which concerns the selection of sources. According to observations, SLDs are well-suited for applications requiring steady performance and good signal quality, as they are more heat-resistant than LEDs and more stable than lasers. Nevertheless, the study has some limitations, despite its benefits. All of the suggested experiments were conducted in a controlled lab, which was vital for replicating the tests; however, this made them less suitable for conditions of humidity, vibrations, or dust outside the lab. Moreover, the study focused on only three types of LEDs; VCSELs and broadband LEDs were outside the subject of this study. Additionally, the research employed temperatures and wavelengths within a narrow range, so the results do not encompass any conditions outside of this spectrum.

4. Conclusions

These findings have practical implications for the design and deployment of fiber-optic sensor systems [51], [52], particularly in industrial sectors across Kazakhstan. Based on the comparative analysis, SLDs are recommended for use in applications where moderate coherence and environmental robustness are critical, such as in oil pipelines, structural monitoring, and remote sensing. LDs should be reserved for applications requiring high precision, where environmental control is feasible. LEDs, while cost-effective, are better suited for short-distance or low-resolution monitoring tasks. By identifying the optimal radiation source for specific environmental and operational conditions, this research supports the development of more resilient and efficient fiber-optic sensor networks in Kazakhstan and other regions with similar climates [53].

This study aimed to evaluate and compare the performance of different radiation sources, specifically LDs, LEDs, and SLDs, when integrated with optical fiber systems [54] under varying thermal conditions. The findings demonstrated that LDs offer superior coherence and signal quality, but are more vulnerable to temperature fluctuations. In contrast, SLDs strike an effective balance between coherence, power stability, and thermal resilience. LEDs, while cost-efficient and thermally stable, displayed limited utility in applications requiring high resolution or long-distance communication. These results directly address the research questions by identifying the operational strengths and weaknesses of each source in the context of environmental variability [55].

4.1. Significance and contribution

It adds significant value to the research on optical sensors, particularly about the growth of industry and environmental concerns in Kazakhstan. Due to the nation's focus on oil and gas exploration, infrastructure maintenance, and the addition of new sensors, it is crucial to accurately identify the best radiation sources.

This research offers valuable insights into sensor placement in challenging environments [56], [57], resulting in a more reliable and trustworthy system. Additionally, the research contributes to the literature by focusing on data from Kazakhstan, where the climatic and industrial settings are unique.

4.2. Future directions

The present research has identified several areas that require further study. It is essential for further studies to:

- Expand the range of radiation sources, including vertical-cavity surface-emitting lasers, broadband LEDs, and photonic crystal-based emitters.
- Conduct extended field trials across multiple climatic zones in Kazakhstan to validate lab-based findings in real-world conditions.
- Explore hybrid systems [58], [59], integrating multiple radiation sources for adaptive sensing applications.
- Investigate long-term reliability and degradation behaviors under continuous operation in harsh environments.
- Integrate the tested sources into functional industrial systems, such as distributed fiber-optic temperature and strain sensors in pipelines, to assess real-time performance and economic feasibility.

Conducting further research will lead to a deeper understanding of technology and help adopt innovative, adaptable, and robust optical systems in Kazakhstan and other regions facing similar environmental challenges.

Declaration of competing interest

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the paper is as follows: Ali Mekhtiyev, Aigul Seraly: study conception and design; Ali Mekhtiyev, Aigul Seraly, Raushan Aimagambetova, Ruslan Mekhtiyev: data collection; Aigul Seraly, Raushan Aimagambetova, Aliya Alkina, Yelena Neshina: analysis and interpretation of results; Yelena Neshina, Ruslan Mekhtiyev: draft preparation. All authors approved the final version of the manuscript.

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