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Investigation of optical spot formation on photomatrix surfaces via continuous optical fiber radiation

Ali Mehtiyev[a1], Kazakhstan Institute of Standardization and Metrology, 11 Mangilik El avenue, Yessil district, Astana city 010000, Republic of Kazakhstan, barton.kz@mail.ru, +77756789999, https://orcid.org/0009-0009-4041-7912
Mohammad G. Rasul [b], Kazakhstan Institute of Standardization and Metrology, 11 Mangilik El avenue, Yessil district, Astana city 010000, Republic of Kazakhstan, alika_1308@mail.ru, +77074919199.

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Abstract

The formation of optical spots on photomatrix surfaces under continuous radiation is a critical factor influencing the performance and reliability of photonic and fiber-optic sensing systems. Despite advancements in fiber-optic technologies, there remains a need for precise methods to analyze spot formation and its impact on sensor accuracy. This study addresses this gap by investigating the characteristics and formation mechanisms of optical spots generated at the output of a single-mode optical fiber under continuous radiation. An intelligent hardware and software system was employed to perform opto-digital analysis of optical spot parameters projected onto a high-resolution photomatrix. The experimental setup involved continuous optical radiation transmitted through a single-mode fiber, with mechanical perturbations inducing micro-deformations that altered the refractive index and modified the spot intensity distribution. Analysis focused on three regions: the fiber core, the core cladding boundary, and the cladding. Results indicate that the cladding region, exhibiting a low-intensity Gaussian distribution, provides the most informative data for monitoring optical losses. Transformation of optical spot images into negative representations enhanced detection sensitivity. These findings demonstrate that selective analysis of specific regions improves the accuracy and robustness of fiber-optic monitoring systems, supporting the development of intelligent sensors for structural health monitoring and other precision photonic applications.

Keywords: Fiber-optic sensors; intelligent systems; optical spot analysis; photonic monitoring; structural health.

* ADDRESS FOR CORRESPONDENCE: Mehtiyev Ali, Kazakhstan Institute of Standardization and Metrology, 11 Mangilik El avenue, Yessil district, Astana city 010000, Republic of Kazakhstan. *E-mail address*: barton.kz@mail.ru / +77756789999

1. INTRODUCTION

The emergence of optical spots on photomatrix surfaces due to continuous optical radiation from optical fibers has substantial ramifications for various photonic applications. Comprehending the dynamics of these optical spots, encompassing their behavior, formation mechanisms, and stabilization under extended exposure to optical radiation, is essential for improving the performance and dependability of photonic devices.

Recent investigations have revealed multiple elements that contribute to the creation of these optical spots, highlighting the significance of environmental conditions. Malyk et al. (2018) emphasize that external factors, especially ionizing radiation, can significantly modify the performance attributes of optical fiber systems. Their findings indicate that the durability of optical layers under different environmental conditions is closely related to the physical and chemical stability of the photomatrix materials. This highlights the need for thorough research of these interactions, since the ramifications go beyond simple optical efficiency to encompass the whole integrity and durability of photonic systems. Interactions between optical radiation and photonic materials also include laser-induced refractive index changes that arise from sustained exposure, influencing local optical characteristics and potentially leading to spot formation and material modification under continuous irradiation (Baba et al., 2025; Chen et al., 2025).

Neftissov et al. (2024) have undertaken significant research on the incorporation of fiber-optic systems in reinforced concrete structures for health monitoring purposes. Their research demonstrates that the particular attributes of optical spots, such as size, intensity, and distribution, directly affect the capacity to evaluate structural integrity. Continuous optical inputs can induce localized heating, leading to stress variations within the photomatrix, which may impact the optical characteristics and, therefore, the operational effectiveness of the monitoring systems. The ramifications of these discoveries for practical applications are substantial, particularly in domains such as civil engineering and structural monitoring, where data retrieval accuracy is crucial.

The generation mechanisms of optical spots are intricately connected to the heat distribution and thermal conductivity of the photomatrix materials. Mekhtiyev, Neshina et al., (2023) present a comprehensive examination of the thermal processes in photonics under continuous optical radiation exposure. Their research indicates that regional temperature gradients can generate unique thermal profiles that affect the refractive index and absorption properties of the photomatrix. Laser irradiation can also alter optical properties such as refractive index and absorption in photonic films over time, with sustained exposure causing structural and optical modifications relevant to spot formation mechanisms (Parida et al., 2023). These phenomena include time-dependent laser interaction effects that underlie more complex spot evolution dynamics in photonic matrices. Zakharchenko et al. (2019) validate these findings by investigating the reaction of several photomatrix materials to prolonged optical exposure, indicating that particular material characteristics, such as thermal stability and optical clarity, are pivotal in spot formation.

The interaction between stress fields and optical radiation adds further complications to the properties of optical spots. Continuous optical radiation alters the microstructural integrity of photomatrix surfaces, necessitating an analysis of the kinetic processes involved in the development and growth of these spots. Comprehending these processes may enable the design of photonic devices with customized attributes, improving their use in various fields like sensing, communications, and energy harvesting.

Investigating the time evolution of these optical spots provides essential insights into their production mechanisms. Divergent investigations have demonstrated that the initial formation phase is governed by quick thermal transients, which evolve into steady-state patterns shaped by the predominant thermodynamic features of the photomatrix. Ongoing research in this field is necessary to determine how these transient occurrences might be utilized or alleviated in practical applications.

The emergence of optical spots on photomatrix surfaces resulting from continuous optical radiation emitted by optical fibers is a complex issue with considerable ramifications for photonic technologies. A comprehensive understanding of the relevant variables and dynamics involved in this phenomenon will be crucial for the progression of photonic applications. The properties of optical spots produced on photomatrix surfaces due to continuous optical radiation from optical fibers have attracted significant interest for their potential in enhancing photonic applications, especially in sensing technologies and health monitoring systems. Recent advancements in intelligent fiber-optic systems are pivotal for facilitating real-time monitoring in diverse engineering fields, therefore requiring an in-depth comprehension of optical spot behavior (Neftissov et al., 2024). These systems employ the exact modification of light propagation to identify alterations in ambient circumstances or physiological parameters, hence highlighting the significance of optical spot characteristics in enhancing sensor performance.

The importance of improved photocured materials in boosting spot stability and functionality has been a focus point in recent research. Advanced composites have been created that enhance the durability and adaptability of optical spots under diverse operational situations (Poothanari et al., 2022). These advancements provide more dependable data collection, essential for applications demanding high precision, such as biomedical diagnostics and environmental monitoring.

Research on the thermal and spectral attributes of sensor architectures has elucidated methods for optimizing optical performance via meticulous adjustment of spot characteristics. Goldina et al. (2016) established that alterations in spot configuration and intensity can markedly affect the sensitivity and selectivity of sensors, hence facilitating improved functionality across many applications. This suggests that additional investigation into the dynamic interactions between optical radiation and photomatrix surfaces is essential for enhancing the performance of photonic devices.

Moreover, systematic issues related to the quantification of thermal parameters continue to represent a significant domain for further investigation. Accurate assessment of these parameters is essential for the effective implementation of optical fibers in actual applications (Tovstonog, 2024; Kant et al., 2023). Resolving these problems would enhance the performance of optical fibers and promote their integration into complex sensor systems functioning under diverse environmental and operational circumstances.

The amalgamation of three-dimensional models and sophisticated imaging techniques signifies novel opportunities for photonics, especially in neurosurgical applications. The integration of optics and engineering paves the way for groundbreaking advancements in health technology, potentially transforming surgical techniques and enhancing patient outcomes (Baranda Castrillo, 2015; Cekic et al., 2025). The capacity to observe and alter optical spots in real-time has ramifications for the accuracy of surgical treatments and may facilitate the advancement of minimally invasive techniques that utilize photonics for improved imaging and targeting efficacy.

The properties of optical spots generated on photomatrix surfaces under continuous optical radiation are crucial for the progression of photonic applications, spanning various fields from environmental sensing to sophisticated medical technology. The continued investigation of these traits is expected to produce substantial innovations, influencing the direction of future research and development in photonics.

1.1. Purpose of study

The purpose of this study is to investigate the formation mechanisms and characteristics of optical spots generated at the output of a single-mode optical fiber under continuous radiation. By analyzing specific regions of the optical spot using an intelligent opto-digital system, the study aims to improve the accuracy and reliability of fiber-optic sensing systems for monitoring optical losses.

2. METHOD AND MATERIALS

The study employed an intelligent hardware–software system (HSS) designed for opto-digital analysis of optical spots projected onto high-resolution photomatrix surfaces, following the methodology described by Neshina et al. (2023) and Mekhtiyev, Neshina et al. (2023). The HSS functions by capturing optical spot parameters, including intensity, amplitude, and spatial distribution, and analyzing changes induced by mechanical perturbations in the optical fiber.

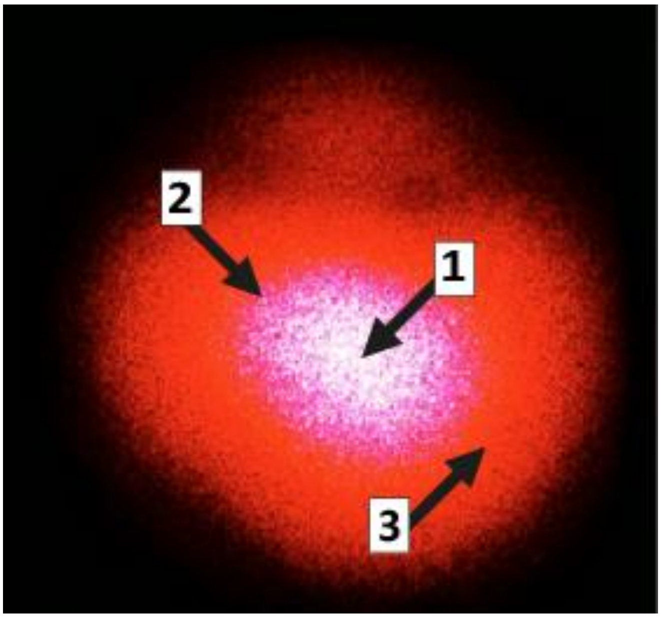
A single-mode optical fiber (G.652 standard) served as the sensor, with continuous optical radiation supplied from a light source operating at a wavelength of 650–670 nm. The output end of the fiber projected the optical spot onto a sensitive photomatrix surface via a transparent screen. Mechanical perturbations were applied to the fiber to induce micro-deformations, altering the refractive index and modifying the intensity and shape of the optical spot. The optical spot was analyzed in three regions: the fiber core, the core-cladding boundary, and the cladding, with emphasis placed on the cladding region, which exhibited a low-intensity Gaussian distribution and provided the most informative data for monitoring optical losses.

The experimental setup included precise alignment of the optical fiber, light source, and photomatrix, ensuring stable continuous illumination and minimizing external disturbances. Image processing techniques, including the transformation of optical spot images into negative representations, were applied to enhance detection sensitivity and facilitate accurate measurement of intensity variations. Data acquisition and analysis were performed using the HSS software, enabling real-time evaluation of optical spot characteristics and their response to mechanical and thermal effects. This methodology allowed for a comprehensive examination of optical spot formation mechanisms, the influence of fiber micro-bending on spot intensity distribution, and the identification of regions within the optical spot most suitable for precise monitoring of optical losses.

The functionality and intelligent data analysis methods for processing signals obtained from fiber-optic sensors were described in detail in Neshina et al. (2023). Mekhtiyev, Neshina, et al. (2023) provide a comprehensive examination of the research methods and previously obtained results, as well as a description of the hardware-software system (HSS). The operating principle of the HSS is based on intelligent opto-digital analysis of the parameters of an optical spot projected onto the surface of a high-resolution photomatrix, followed by analysis of changes in the amplitude and intensity of the optical wave. Figure 1 presents a visualization of the optical spot intensity, its key characteristics, and the influence of additional optical losses caused by micro-bending in the optical fiber.

Figure 1

Visualization of the optical spot radiation intensity



1 – radiation intensity in the fiber core; 2 – radiation intensity at the core–cladding boundary, noise formation zone; 3 – radiation intensity in the cladding region.

3. RESULTS

On one end of the optical fiber (OF), which serves as the sensor, a light source with a wavelength of 650-670 nm is installed. On the opposite end of the OF, a high-resolution photomatrix is placed, onto which the optical spot is projected. The radiation is transmitted continuously through a single mode of the G652 standard. The optical radiation propagates through the OF and falls onto the sensitive surface of the photomatrix, where the image is formed. Mechanical impact on the OF causes deformation that results in a change in the refractive index, which in turn leads to variations in the shape and intensity of the optical spot. When a lateral mechanical force is applied to the fiber, the parameters of the optical radiation are altered and recorded by the monitoring system. The optical spot is formed at the fiber end face, passes through a transparent screen, and is projected onto the photomatrix. The most informative areas include the core-cladding boundary and the cladding itself. The transition boundary where the light wave passes from the core into the cladding represents a region of significant complexity. Similar to the core, this zone is subject to numerous disturbances that negatively affect the performance of the hardware-software system (HSS), necessitating active suppression. Zone 2 is characterized by radiation intensity in the boundary region between the core and cladding, where noise is formed. The HSS focuses on the third region of the optical spot, which resembles a Poisson spot and follows a Gaussian distribution. The radiation intensity in the cladding (Zone 3) is the lowest compared to other regions and is used for opto-digital analysis (Mekhtiyev, Neshina, et al., 2023).

The investigation of optical spots generated on photomatrix surfaces by continuous optical radiation supplied via optical fibers is a crucial domain of research, particularly within the realm of photonics. The development of these spots entails complex interactions between the optical fibers and the photomatrix surfaces, shaped by the characteristics of the transmitted radiation. Optical fibers are progressively employed for their capacity to transfer light effectively over extensive distances. Continuous optical radiation traversing these fibers transfers energy to the photomatrix surfaces, resulting in localized heating and energy deposition. This approach facilitates the creation of optical spots, defined by unique intensity distributions and thermal profiles (Malyk et al., 2018). The fundamental mechanisms encompass multiphoton absorption and thermal diffusion, which can be influenced by the characteristics of the photomatrix material, such as its optical density and thermal conductivity.

The attributes of optical spots can be affected by several factors, including the wavelength of the transmitted light, power levels, and exposure period. Spot formation frequently results in alterations to the surface morphology of the photomatrix, which can subsequently influence its photonic properties (Tomashuk et al., 2018). Recent improvements in the field have underscored the significance of intrinsic radiation-induced defects, such as self-trapped holes, which can facilitate these alterations under particular conditions (Rickelt et al., 2016). Moreover, these optical spots have significant consequences for practical applications. The advancement of fiber-optic systems for assessing structural integrity and health has garnered interest in civil engineering. Studies indicate that fiber-optic sensors can proficiently monitor load-bearing structures and identify irregularities, hence improving the safety of civil constructions (Mekhtiyev, Narkevich, et al., 2023). Likewise, applications in environmental monitoring, such as evaluating the stability of pit collapses, demonstrate the adaptability of fiber-optic technology in transmitting real-time data (Neshina et al., 2023).

The incorporation of optical fibers into phototherapy methods has demonstrated their promise in medicinal applications. Research examining the efficacy of phototherapy has demonstrated that accurate illumination, enabled by fiber-optic systems, can enhance patient results (Zakharchenko et al., 2019). The capacity to produce precise optical spots improves therapy efficacy, highlighting the significant ramifications of research on optical spots.

The ongoing advancement of fiber-optic technology, along with advancements in photomatrix materials, indicates a favorable future for enhancing the production and application of optical spots. Future studies should seek to clarify the mechanisms regulating spot development and heat interactions on photomatrix surfaces. These breakthroughs will not only augment our comprehension of photonics but also improve practical applications in diverse domains, including infrastructure monitoring and medical therapy (Neftissov et al., 2024). The inquiry into optical spots on photomatrix surfaces uncovers intricate connections facilitated by continuous optical radiation using optical fibers. Characterizing these locations and comprehending their ramifications is essential for leveraging their potential in many applications, facilitating novel solutions in engineering and health.

For subsequent analysis, the optical spot is initially represented as a positive image, which is then converted into a negative by the HSS. This transformation enables more effective analysis of light-wave losses occurring in the cladding. The process utilizes the intelligent capabilities of Python-based software.

4. CONCLUSION

This study investigated the formation mechanisms and characteristics of optical spots generated at the output of a single-mode optical fiber under continuous radiation. By employing an intelligent hardware-software system for opto-digital analysis, it was shown that selective examination of the cladding region provides the most informative data for monitoring optical losses.

The results demonstrate that mechanical perturbations influence spot intensity and distribution, and that image processing techniques can enhance detection sensitivity. These findings support the development of more accurate and reliable fiber-optic sensing systems, with potential applications in structural health monitoring, environmental sensing, and precision photonic technologies.

Conflict of Interest: The authors declare no conflict of interest.

Ethical Approval: The study adheres to the ethical guidelines for conducting research.

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