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Impact of environmental conditions on the signal of 650 nm semiconductor lasers

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Abstract: This study investigates the influence of various environmental factors, particularly temperature, relative humidity, smoke, and dust particles, on the optical output power (P) of a 650 nm semiconductor laser. The effects of environmental factors on beam transmission are experimentally investigated with embedded messages and without. The experiments are conducted with a laser under different environmental factors to simulate typical operating conditions for optical devices. The results show that the transmitted signal with the message gradually decreases in P from 317.5 µW to 255.2 µW with increasing temperature from 28 °C to 55 °C. When the relative humidity increases from 10% to 80%, the P decreases from 245.3 µW to 67.5 µW similar to the case of the temperature effect. However, with the massage scenario humidity less affected the laser signal. Furthermore, when measuring the P at a smoke concentration of 182 ppm to 268 ppm, its value decreases from 305.4 µW to 54.4 µW, which shows less effect than temperature and humidity. The dust density used in the channel is 8.57 mg/m^3 to 208.44 mg/m^3 to simulate different amounts of airborne particles found in various environments to study their effect on the signal. The power signal has decreased dramatically as the dust concentration increases, with and without massage. As observed from the results, smoke concentration has a minimal impact compared to other factors, temperature fluctuations, humidity, and dust density. These results give useful information for applications that used transmitting data under similar environmental conditions, making this work suitable for providing insights into different atmospheric conditions.

Keywords: *Free space optical communication (FSO), Humidity effects, Semiconductor lasers, Smoke effects, Dust density, Temperature effects.*

1. Introduction

650 nm wavelength is widely used in short-range optical communication systems [1, 2] and consumer electronics such as laser pointers, barcode scanners, and optical drives, which are part of normal life [3]. Visibility and inexpensive diodes make this a practical wavelength. 650 nm lasers enable short-distance data transmission that works well when traditional fiber optic wavelengths such as 1550 nm are impractical, particularly for communications systems [4]. However, 650 nm lasers are known to be very sensitive to environmental conditions. For obvious reasons, temperature changes lead to changes in wavelength and consequently a reduction in laser power, possibly due to the intended true mode structure. Too high humidity can lead to scattering and absorption of the laser beam leads to reduced transmission distance due to signal attenuation. The particles in the air (smoke particles, etc.) can scatter and weaken the laser light, potentially causing further signal loss or quality degradation [5, 6]. Controlling these environmental factors is critical to the robust operation of 650nm lasers in communications systems, providing stability and accuracy to assist when needed.

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1.1. Semiconductor Lasers in Free Space Optical Communication

Free-space optical (FSO) communication is considered to be an important solution for the shortage of standard radio frequency and millimeter-wave technologies and has been gradually realized in scientific applications [7]. The FSO offers high-speed data transfer and secure transmission, and it is also highly energy-efficient. Semiconductor lasers, a crucial component of FSO technology, enable light modulation and data transmission over long distances without requiring any specific physical channel infrastructure. The directional stability and narrow beam of semiconductor lasers are used to nearly align the laser beams at both ends in FSO systems so that high-quality communication links can be built.[8, 9]. The optical properties of the semiconductor laser are sensitive to environmental changes, which lead to large fluctuations in its performance and stability. Some key parameters that affect their performance are:

Temperature: It changes the bandgap of the semiconductor material, shifting the output wavelength and affecting the efficiency of the laser. Higher temperatures can introduce additional charge carriers into the laser cavity, resulting in thermal noise and shortening device life.[10].

Humidity: This can result in condensation on laser components, especially on optical facets, which can contribute to scattering losses and deterioration of the laser output [11].

Smoke: Could either absorb or deflect laser light. This can be particularly harmful in FSO systems, where the quality of the laser beam is important. The collection of these particles can potentially result in physical harm to the laser facets [12]. Variety in air temperature causes fluctuations in the refractive index along the path of the laser beam. Transmitting signals in atmospheric turbulence generates distortion and affects the alignment of FSO communication systems [13, 14].

Dust Density: The dust is defined as a group of rare particles in the center of Ghazi that may contain air. Aerial plankton can also occur in the air in the form of dust, sparse spray or smoke[15]. When dust particles are longer than circular, they exhibit an exotic effect of effective attenuation, which is important for attenuating electromagnetic radiation. These plankton flights can affect attenuation, a reduction in the strength and intensity of sunlight, caused by atmospheric dust or plankton air (aerosol) if the particles are sufficiently scattered [16] .

Although there are numerous studies on the fundamental characteristics and uses of semiconductor lasers with different environment. There is still a limited understanding of how they work in challenging environmental conditions, especially in the context of FSO systems. The main goal of this study is to find out how different environmental factors affect the performance of 650 nm semiconductor lasers, especially when they are used in FSO communication systems [17].

2. Literature Review

The study proposed by Hasirlioglu et al.[18] investigates the effect of exhaust gases at low temperatures on optical systems, specifically concentrating on the implications of smoke plumes with high humidity. Their findings illustrated how these environmental determinants can significantly degrade the performance of sensors operating at 650 nm wavelength. However, the investigation left some gaps, as it did not consider the combined implications of other factors, such as dust and humidity, which are critical for comprehending the full environmental effect on optical systems. Another study was published by Carrico et al. [19] studied the influence of smoke particles on light scattering and absorption at 650 nm. Their tests showed that the influence of smoke, especially in environments with changing humidity and temperature, significantly reduced light penetration while severely affecting the precision of the sensor.However, the study primarily focused on long-term responses to aged smoke particles rather than the short-term implications of fresh smoke emissions, leaving a gap in interpretation of the immediate effect of smoke.

Deng et al.[20] have found that the black smoke significantly reduces light transmission and affects sensor sensitivity at 650 nm. However, the study only tested black smoke and did not test other types of smoke, leaving room for further research. While, Stajanca et al. [21] explored the impact of humidity on wavelength transparency in optical systems, where demonstrating that the relative humidity fluctuations directly affect performance of the system. However, the study did not evaluate the long-term stability of optical systems under extreme environmental conditions like continuous exposure to high humidity.

Also, The research by Zhao et al. [22] studied the operating temperature of fiber optic sensors in response to temperatures ranging from 20 °C to 650 °C, highlighting the significant impact of changes in sensor operating conditions on performance and emphasizing the importance of proper temperature control in optical configurations. However, there is currently no documentation on how cyclic temperature changes can impact the long-term stability of these sensors and potentially shorten their lifespan. He et al. [23]focused on the effect of humidity on light intensity in optical systems and showed that increased humidity led to reduced visibility and therefore poorer performance. This study did not examine the effects of combined variables such as dust or simultaneous changes in humidity and temperature that could degrade system functionality. Finally, Baró Pérez et al. [24]investigated how smoke, humidity and temperature affect the performance of optical systems at 650 nm. They found that high humidity in smoke clouds, especially when low-temperature exhaust gases were present, had a major impact on optical properties.

3. Methodology

3.1. Experimental Setup

In this study, we used a chamber measuring 2 * 0.50 * 0.50 m in length and width and height respectively, to investigate the effects of temperature, humidity, and smoke on the efficiency of a 650 nm semiconductor laser. We constructed an experimental arrangement that can replicate different environmental circumstances. This arrangement includes both sender and receiver elements, along with an intermediary chamber specifically designed to control environmental factors. Figure 1 shows the practical chamber setup.

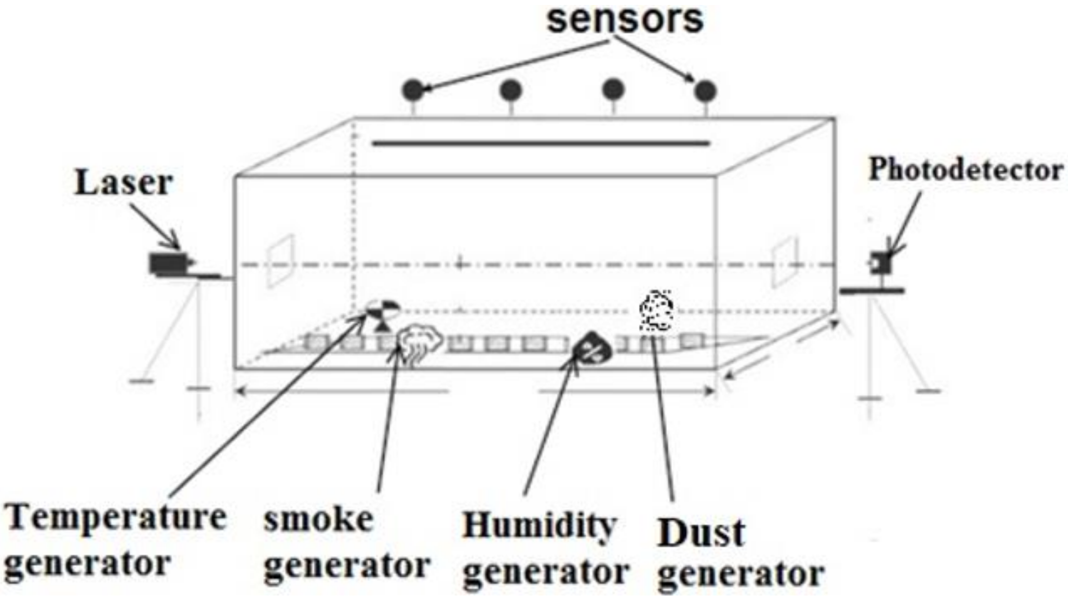

Figure 1.
Practical chamber setup.

3.1.1. Transmitter Side. The Transmitter Side Consists of the Following

A 650 nm laser diode, Arduino Uno, this is a microcontroller board that uses the ATmega328P chip, which has 14 digital input/output pins, 6 analog inputs, a 16 MHz quartz crystal, a USB connection, power socket, and an ICSP header. It manages the operation of the lasers and analyzes data collected by sensors in the receiver side. Computer laptop utilized for programming the Arduino Uno and for gathering and analyzing data.

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3.1.2. Channel (Chamber) Consist of the Following

MQ-2 Gas Sensor Module: Used to detect smoke and combustible gases, Heat Generator Device: Used to control the temperature within the chamber. Humidity Generator: Used to control the humidity levels within the chamber. Smoke Generation Device Using Coal: Used to generate smoke for the experiments. PM2.5 GP2Y1010AU0F Dust and Smoke Particle Sensor: Used to measure the concentration of dust and smoke particles within the chamber.

3.1.3. Receiver Side

A silicon photodiode, (Si PIN) is used to detect the light signals emitted by the lasers. The Arduino Uno is responsible for processing data obtained from the photodetector and other sensors. Computer Laptop: utilized for programming the Arduino Uno and conducting data gathering and analysis. A digital thermometer is used to measure both temperature and humidity. Solar Cell: A 1W solar cell with dimensions of 110mm x 60mm and a current of 100mA. The system uses valuate the impact of light intensity. The oscilloscope is used to visually analyze the waveforms of the signals received from the photodetectors and to quantify the output voltage.

The setup: In order to control the lasers and gather sensor data on both the transmitter and receiver sides, an Arduino Uno was first used. The Arduino Uno's transmitter side should be connected to the laser, sensors on the receiving end and laser alignment with the photodetector. Environmental Control: First, we placed the transmitter and receiver installations in the chamber. Next, Utilize the PM2.5 sensor for the purpose of monitoring the levels of dust and smoke. we used the MQ-2 gas sensor to detect the smoke concentration. The heat generator then regulates the temperature. The humidity generator also adjusts the humidity. Finally, to produce smoke, we used the smoke generator with coal.

Data Collection: We calculate output voltage (V) and the optical output power (P) for various environmental parameters (temperature, humidity, smoke and dust.), with and without an embedded message on the laser. We performed additional measurements using message-carrying laser signals. The oscilloscope is used to display signal waveforms and measure the output voltage.

Data Recording: Using a laptop connected to the Arduino Uno, record each V value and P value of the power meter. A temperature range of 28°C to 55°C was used in this experiment because many electronic and optical devices operate within the normal ambient and operating temperature range. It is important to understand how power varies across this spectrum because higher temperatures can affect the stability and efficiency of semiconductor lasers.The implications of this temperature swing were then thoroughly discussed. Additionally, we took these readings between 10% and 80% of humidity, this range was selected to evaluate the laser's resilience in various atmospheric situations, including both dry and humid conditions. . Moreover, the amount of smoke was progressively raised from 182 to 268 parts per million (ppm), and the alterations that occurred were closely observed. Dust density has a large impact on performance metrics, with “with message” performing better than “without message embedding.” Embedding messages can be beneficial in high dust situations, the range for Dust density was 8.57 mg/m^3 to 204.44 mg/m^3. The collected data was then saved for later examination under environmental parameter conditions.

The investigation procedure is as follows in the flowchart in Figure 2.

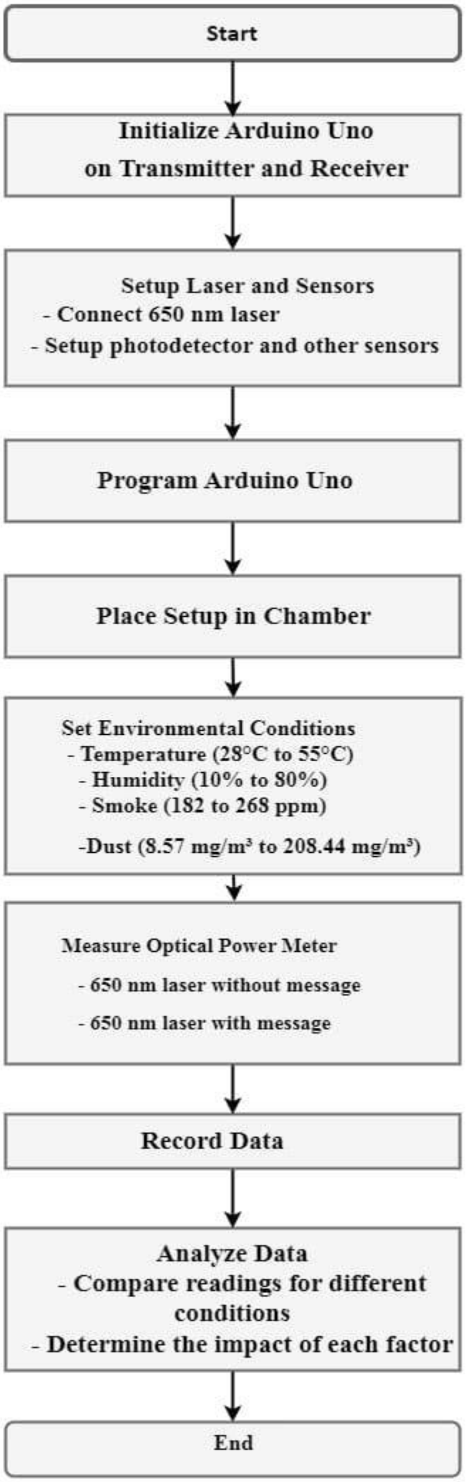

Figure 1.
The flowchart for the study.

Data Analysis: Analyze all of data that was gathered carefully to find out how the laser's performance affected by each environmental factor. Examine the differences between the laser’s outcomes with embedded messages versus those without.

4. Result and Discussion

The P of the laser has been measured with and without embedded messages, which has been investigated as a function of environmental conditions. The results obtained from the laser with and without messages provide valuable insights into the stability and performance of this device. Table 1 shows the performance of the laser under different environmental conditions, both with and without message transmission. These conditions were selected to represent real-world scenarios where temperature, humidity, smoke, and dust could impact laser performance. When the temperature changes from 28°C to 55°C, the voltage output decreases significantly during message transmission, dropping from 3.9V to 2.6V, while the idle state (without message transmission) ranges from 11.3V to 9.93V. This temperature range was chosen from typical room temperature and the extreme operational conditions in our lab. The P during message transmission also shows an increase, ranging from 255.2 μW to 317.5 μW, compared to 229.2 μW to 284.5 μW in the case without massage. The higher temperatures contribute to increased signal attenuation and component heating, which explains the voltage and power variations.

For humidity, a range of 10% to 80% was selected to cover conditions from very dry air to highly humid environments in the lab, mimicking desert and tropical conditions, respectively. As humidity rises, V drops from 10.35V to 2.12V without message transmission, and from 3.9V to 1.9V with message transmission. Similarly, P falls from 245.3 μW to 67.5 μW without an embedded message, and from 265.1 μW to 83.8 μW with the message transmission. Although both scenarios show a decline, message transmission leads to slightly higher power readings. The drop in performance at higher humidity levels is likely due to the increased water vapor in the air, which can scatter the laser light and reduce signal efficiency.

Smoke concentration, measured from 182 ppm to 268 ppm, reflects typical indoor air pollution levels and industrial smoke conditions. As the concentration increases, both V and P drop sharply. Without message transmission, it drops from 11.51V to 1.22V, while with the message it drops from 3.9V to 1.7V. P also decline, from 245.4 μW to 64.4 μW without a message, and from 305.4 μW to 83.3 μW with the message. Higher smoke concentrations increase the scattering and absorption of the laser beam, leading to significant losses in output power.

Dust density, ranging from 8.57 mg/m^3 to 208.44 mg/m^3, was chosen to simulate conditions from relatively clean air to heavy dust storms or construction site conditions. Without message transmission, V drops from 10.8V to 1.72V, while with message transmission, it drops from 5.2V to 1.6V. The P also shows a decrease, from 241.2 μW to 50.9 μW without massage, compared to 325.7 μW to 87.3 μW with the message. In high-dust environments, the scenario with the message consistently outperforms the scenario without the message in terms of power, suggesting that message embedding may provide better signal resilience in these conditions. The attenuation and scattering of the laser beam caused by dust particles likely explain the observed performance drop.

Overall, the ranges for each environmental condition were chosen to cover a broad spectrum of possible real-world scenarios, from moderate to extreme, allowing a comprehensive analysis of the laser's behavior in various operational environments. The degradation in voltage and power under harsher conditions can be attributed to increased attenuation, scattering, and interference caused by temperature, humidity, smoke, and dust. The experimental data covering all cases considered in this study are shown in Figure 3.

Table 1.
Results of laser 650 nm without and with the message transmission.

Condition	Range	V(output) Without Message (V)	Power Meter Without Message (μW)	V(output) With Message (V)	Power Meter With Message (μW)
Temperature (°C)	28°C to 55°C	11.3V to 9.93V	284.5 μW to 229.2 μW	3.9V to 2.6V	317.5 μW to 255.2 μW
Humidity	10% to 80%	10.35V to 2.12V	245.3 μW to 67.5μW	3.9V to 1.9V	265.1μW to 83.8μW
Smoke (ppm)	182 ppm to 268.ppm	11.51V to 1.22V	245.4 μW to 64.4 μW	3.9V to 1.7V	305.4 μW to 83.3μW
Dust(mg/m³)	8.57 mg/m³ to 208.44 mg/m³	10.8V to 1.72V	241.2 μW to 50.9 μW	5.2V to 1.6V	325.7 μW to 87.3 μW

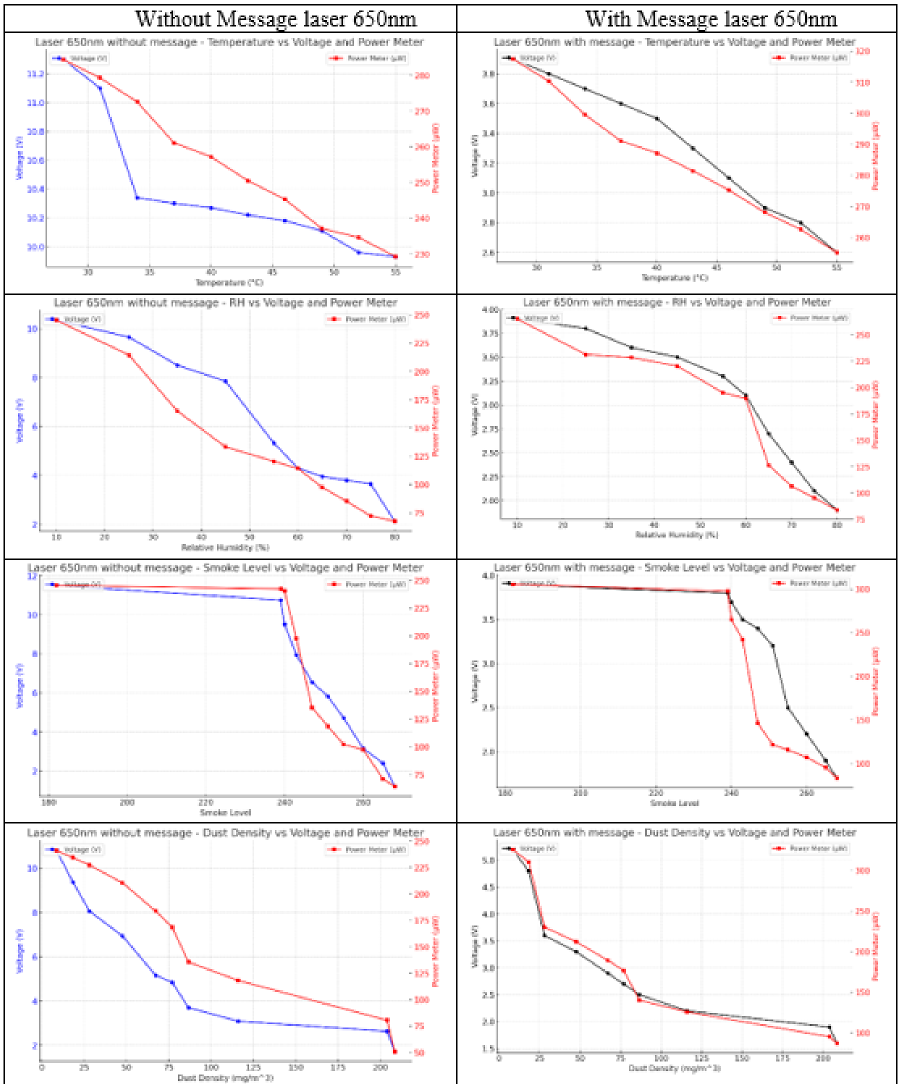

Figure 3.
The 650nm laser performance under different environmental conditions.

The radar chart presented in Figure 4 illustrates that, for every environmental factor (temperature, relative humidity, smoke, and dust), the "With Message" scenario consistently yields higher power compared to the "Without Message" scenario. Message embedding appears to have a significant positive impact on laser performance across various environmental conditions. The largest differences are observed at high levels of smoke and dust, where the case with the message demonstrates greater resilience and maintains higher power output. This suggests that the laser system is more sensitive to environmental interference when operating without message embedding, especially in harsh conditions like high dust density and smoke concentration.

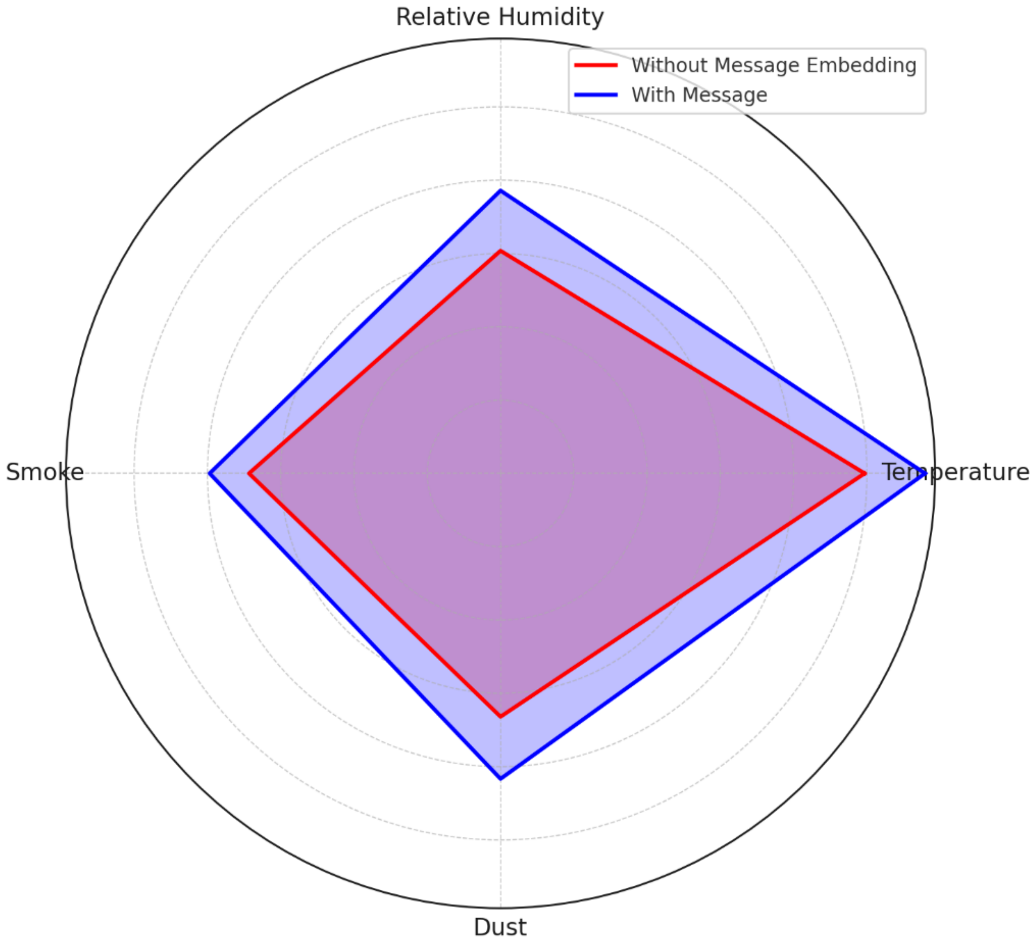

Figure 4.
Average power response with different environmental effects.

5. Discussion

The experiments were conducted under various environmental conditions, demonstrating substantial effects on the performance of the 650 nm laser. The parameters examined by temperature, relative humidity, smoke concentration, and dust density are essential for evaluating the stability and dependability of such lasers across different operational environments, especially for applications like sensing and optical communications.

1. The influence of temperature was that V and P decrease with increasing temperature. The laser shows a linear downward change during both message delivery and splitting, indicating decreasing efficiency as temperatures increase. However, the results show a greater degradation of V during message communication, suggesting that increased temperatures significantly affect the output voltage

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and power during message transmission. This behavior highlights the importance of developing efficient cooling mechanisms when outside temperatures fluctuate or become high.

2. *Relative humidity: which has an equally significant effect on laser performance. The rise of humidity causes a marked reduction in both V and P, especially without message transmission. This trend hints that optical elements were also sensitive to humidity. However, the results suggest that the messaging function performs marginally better in moist environments.*
3. Smoke Concentration: Smoke concentrations were varied to assess their effect on visibility and laser performance. The amount of smoke in focus affects the laser performance. Without the messaging function, V and P drop significantly as smoke concentration increases. Smoke particles scatter the laser beam, resulting in inefficiency due to energy dissipation before reaching the target. This scattering reduces the effectiveness of the laser in applications such as communication systems and sensors. The presence of smoke makes it difficult for the laser to remain strong and effective, especially in smoke-heavy environments like wildfire zones
4. *The Dust Density Effect: Dust particles both scatter and absorb laser light, hence diminishing power and signal strength. As dust density escalates, the laser beam diminishes in strength owing to an increased number of particles inducing signal distortion. This results in diminished performance, signifying a decline in transmission efficiency and increasing the danger of data tampering. The particles in dust obstruct laser transmission by absorbing and dispersing light in several directions.*

6. Conclusion

The experiments show that the 650 nm laser works under different environmental conditions such as temperature, humidity, smoke and dust. Under these conditions, the laser experiences a significant reduction in output voltage (V) and optical power (P). While the message transfer function shows a slight decrease in P, indicating an obvious increase in energy demand during message transfer, low relative humidity also reduces V and P, although the message function provides some buffering. However, the greatest drop in performance occurs when smoke is high, while the scattering and absorption of dust particles severely affects the laser. This scattering reduces the direct transmission of light from the transmitter to the receiver, resulting in a drop in V and P.

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