



Experimental Study of the Performance of a 650 nm Semiconductor Laser on an Atmospheric Channel

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Article Info

Article history:

Received 05, 06, 2025

Revised 06, 20, 2025

Accepted 08, 14, 2025

Published 10, 30, 2026

Keywords:

Semiconductor laser,
650 nm wavelength,
free-space optical,
Arduino Uno, data transmission,
atmospheric influence.

ABSTRACT

The research evaluates a 650 nm semiconductor laser system operating in different air conditions by analyzing temperature and humidity levels and smoke and dust density effects. The study analyzed laser performance both with and without data transmission to determine how operating conditions and environmental disturbances affect the system. The purpose of this study is to assess the effects of temperature, humidity, smoke, and dust on a 650 nm semiconductor laser's performance in free-space optical communication, both with and without data transmission. In order to monitor laser output under regulated conditions, the experimental methodology used an Arduino Uno platform integrated with optical power measurement tools and environmental sensors (temperature/humidity, MQ-2 gas sensor, and GP2Y1010AU0F dust detectors). Significant power deterioration with increasing environmental disturbances is demonstrated by the following key results: output decreased from 102.4 μW to 92.8 μW without messaging and from 292.1 μW to 142.3 μW with messaging when the temperature rose from 12°C to 45°C; Message transmission raises the initial power but increases the vulnerability to atmospheric impacts; dust density (714 mg/m^3) and excessive humidity (99%) resulted in nearly total signal loss. Measurements were made indoor and outdoor also SNR, BER, and Scintillation were calculated. The importance of adaptive modulation approaches in FSO systems working in difficult conditions is shown by these findings.

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1. INTRODUCTION

The advantages of semiconductor lasers include their small size and weight, high efficiency, and ease of modification. Currently, these types of lasers are applied in precision measurement [1], environmental monitoring [2], gas detection [3], among others. This research examines the impact of temperature, humidity, dust, and smoke on the functioning of a 650 nm semiconductor laser. This research analyzes the environmental factors that change the output of the laser within a controlled environment equipped with environmental sensors and optical power meters. The 650 nm wavelength laser is beneficial in free-space optics systems since it is in the visible spectrum, thus providing clear sight and cost-effectiveness [4,5]. This work enhances the dependability of laser communication systems in diverse atmospheric conditions.

Ensuring laser systems are dependable under different environmental conditions is very important for applications like optical communications. Signal attenuation, signal degradation, and measurement errors occurring because of temperature changes, humidity, dust, and smoke are significant challenges to lasers. This dissertation focuses on a 650 nm semiconductor laser, which is preferable for free-space optical communications because it is visible and efficient. The study focuses on the output of the laser over different

harsh atmospheric conditions to advance laser systems that work reliably even in extreme and challenging environments [6].

This investigation starts with examining the most recent studies concerning the ecological impact of semiconductor lasers operating at a wavelength of 650 nm. The research by Garlinska et al. [7] evaluated FSO links at 1.55 μm and 10 μm wavelengths to show that 10 μm offers better stability and stronger signals in fog and light rain conditions while providing better eye safety and environmental resistance. Al-Gailani et al. [8] performed a comprehensive evaluation of free space optical (FSO) systems by analyzing single-beam and multi-beam architectures under heavy rain and haze conditions. The authors developed a hybrid DWDM/multi-beam FSO system which supports 16–32 channels to enhance scalability and reduce link degradation while meeting future deployment requirements. Cao et al. [9] studied laser transmission in sandy-dust environments by using radiation propagation and small-angle approximation methods to show that multiple scattering causes pulse delay and attenuation which can be reduced by using longer wavelengths. The research by Ghoname et al. [10] evaluated free space optics (FSO) at 850, 950 and 1550 nm wavelengths under fog, rain and humidity conditions to show that the 1550 nm wavelength with a 15 cm receiver achieved the lowest bit error rate (BER) and best link margin at 1 km distance when using non-return-to-zero on-off keying (NRZ-OOK) and a PIN photodiode.

This paper is organized as follows: Section 2 reviews the theoretical equations, Section 3 describes the methodology and experimental setup, Section 4 presents and analyzes results, and Section 5 concludes with future research directions.

Theoretical and Conceptual Framework

Total attenuation the atmospheric attenuation of an FSO system is primarily influenced by haze and fog and is also contingent upon precipitation. Total attenuation include air attenuation and geometric loss. The overall attenuation for an FSO system is fundamentally straightforward at a macro level, excluding factors such as optical efficiency and detector noise. The total attenuation is represented by the following [11]:

$$\frac{P_r}{P_t} = \frac{d_2^2}{[d_1 + L\theta]^2} \times \exp(-\beta L) \dots \dots \dots (1)$$

Where: P_t is the transmitted power (unit: mW); P_r is the received power (unit: mW); θ is the beam divergence (unit: mrad); β is the total scattering coefficient (unit: km^{-1}). According to Equation (1), the controllable variables include aperture size, beam divergence, and link range. The dispersion coefficient is unmanageable in an outdoor setting. In actual atmospheric conditions, with availabilities of 99.9% or higher, the system designer may opt to utilize substantial transmitter laser strengths, create large receiver apertures, build tiny transmitter apertures, and implement little beam divergence. Another element that can be controlled is link range, which should be limited to a low distance to ensure that air attenuation does not predominate in the overall attenuation [12].

Refractive Index Variations there are numerous C_n^2 profile parametric models, with one of the most popular being Hufnagel-Valley . It is expressed as follows [13]:

$$C_n^2(h) = 0.00594 (v/27)^2 (10^{-5}h)^{10} \exp\left(-\frac{h}{1000}\right) + 2.7 \times 10^{-16} \exp\left(-\frac{h}{1500}\right) + A_0 \exp\left(-\frac{h}{100}\right) \dots \dots \dots (2)$$

Where h : Is related to the height above the sea level, expressed with the metric unit of meters (m). v : Describes the speed of wind at high altitudes, measured in meters per second (m/s). A_0 : Shows the level of turbulence close to the ground, $A_0 = 1.7 \times 10^{-14} \text{ m}^{-2/3}$. Its variation is mostly influenced by wind and altitude. The most important effects of turbulence on an optical beam are beam scattering, beam shift, and scintillation.

SNR (Signal-to-Noise Ratio) and BER (Bit Error Rate) The efficacy of a communication system is often evaluated with regards to its Signal-to-Noise Ratio (SNR) and Bit Error Rate (BER). Increasing the received optical power and reducing scintillation effects are possible with proper aperture averaging design. With turbulent SNR, it can be represented as follows [14]:

$$SNR = (0.31 C_n^2 K^{7/6} L^{11/6})^{-1} \dots \dots \dots (3)$$

Where C_n^2 Refractive index structure (units: $\text{m}^{-2/3}$). And K is the optical wave number $K = \frac{2\pi}{\lambda}$. While L is the propagation path length (units: meters, m).

The expression for the Bit Error Rate (BER) in relation to Free Space Optical (FSO) links utilizing the On-Off Keying (OOK) modulation technique is stated below [14]:

$$BER = \frac{\exp\left(-\frac{SNR}{2}\right)}{(2\pi SNR)^{0.5}} \dots \dots \dots (4)$$

Scintillation Index the power level (amplitude) of the beam σ_i , which is provided by the following formula, can be used to quantify the scintillation strength:

$$\sigma_i^2 = 1.23 C_n^2 K^{7/6} L^{11/6} \dots (5)$$

Equation (5) for the weak turbulence condition is $\sigma_i^2 < 1$. The type of electromagnetic wave moving through turbulence and the description of the link geometry determines the expression of the lognormal field amplitude variance [15].

Experimental Setup and Methodology

A structured experimental setup was designed to study the performance characteristics of a 650 nm semiconductor laser under various environmental conditions. The research aimed to determine how temperature changes and humidity conditions and smoke exposure affect the laser output power. The study used precise instruments together with advanced measurement techniques to ensure accurate data collection and maintain uniform control of all experimental parameters as shown in Figure 1.

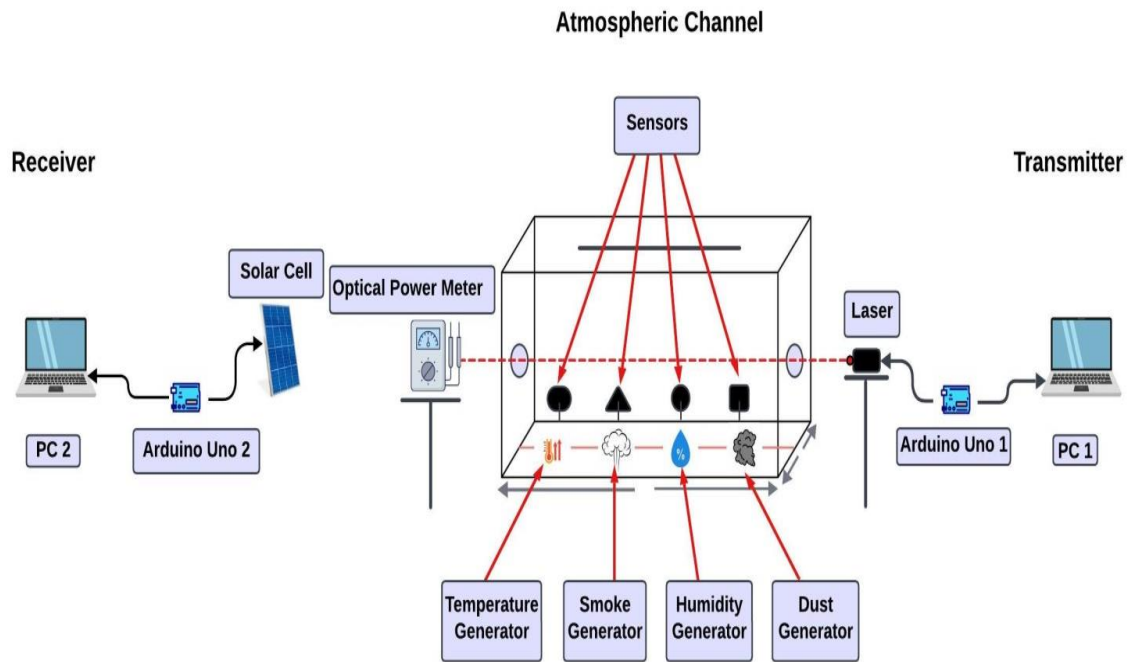


Figure 1. Schematic Diagram of the Simulated Atmospheric Channel Experimental Setup.

Laser Modules

This research incorporates a semiconductor laser operating at 650 nanometers with a 100 milliwatt output power. Applications such as optical data transmission, medical diagnostics, and electronics aided in the selection of the 650 nm laser as it works within the visible spectrum. The alignment of experimental arrangements is enhanced with the visibility of red light at 650 nm [14].

An adjustable platform was used to mount the laser module so it could be optimally positioned relative to the optical power and additional critical optical elements of the experiment. The system under test provided stable and accurate beams and precision during the experiment, and good reproducible outcomes were obtained.

Environmental Sensors

Environmental sensors were used for monitoring the temperature and humidity to ensure conditions were stable and within a specific range for precision testing of the 650 nm semiconductor laser:

1. **Temperature Sensor:** An ambient temperature check using a digital thermometer was performed in the experimental setup. The system permitted the continuous collection and reliable data necessary to research the effect of temperature and elevation on the output characteristics of the 650 nm semiconductor laser, known for its sensitivity to thermal and emissive changes [16].
2. **Humidity Sensor:** An atmospheric data collection system hosts a digital humidity sensor which monitors the environmental conditions that influence the result of a 650nm semiconductor laser. The system allowed for a continuous monitoring of relative humidity which provided critical data for moisture-laser performance dependence. The information gathered in Figure 2 supports the

investigation on humidity effects on laser optics degradation, such as contamination of the facets and deterioration of the beam.

3. **Smoke and Dust Density:** The MQ-2 gas sensor is used for smoke detection as shown in Figure 3. Five GP2Y1010AU0F dust sensors [17] to measure dust concentration. The sensing chamber was equipped with five GP2Y1010AU0F optical dust sensors to measure PM2.5 concentrations in real time because these sensors provide reliable and compact detection of airborne fine particles. The combination of these elements allowed for a complete evaluation of the laser beam attenuation properties under different particle conditions which led to an accurate relationship between PM concentration and optical signal degradation [18].

Data Acquisition and Control System

1. **Arduino Uno Microcontroller,** The Arduino functions as both the control and data gathering unit. Its adaptability and seamless integration render it an optimal platform for connecting with many sensors and measuring instruments. The Arduino was built to gather data from various environmental and optical sensors, including temperature, humidity, smoke, dust sensors, and a power meter for monitoring laser output power.
2. **Optical Power Meter:** The study evaluated the optical output power (P) under various environmental conditions (temperature, humidity, smoke, and dust) with and without embedded message on the laser. We conducted further measurements utilizing message-bearing laser pulses [19].

Experimental Protocols

The experimental methods took place in a controlled setting which enabled researchers to modify temperature, humidity, Dust and smoke concentration levels for performance system analysis. The process required the following successive steps:

1. **Temperature Variation:** The experimental chamber underwent a temperature transformation from 12 °C to 45 °C to determine its effect on laser power transmission. The power output of three lasers with different wavelengths was measured at each temperature point using a power meter. The Arduino system monitored temperature data from connected sensors which would be analyzed later.
2. **Humidity Variation:** The experimental humidity sensor was operated at various humidity levels ranging from 10% to 99% to study their effect on laser output and performance. The laser power output was measured sequentially with a power meter at each humidity setting.
3. **Smoke and Dust Concentration:** The experiment chamber received the smoke effect via a control system to create a smoke environment with controllable quantities. An MQ-2 gas sensor [20] and a PM2.5 dust sensor connected to an Arduino Uno tracked smoke concentrations and dust particle levels within the system. The laser output power was measured using power meter readings to determine the effect of these particles.

Experiments were conducted and repeated several times to ensure the reliability and validity of the data, and the results were averaged to reduce the effect of irregularity and error in measurements.

Data Analysis

All data from sensors and measuring instruments was analyzed to determine the effect of light, moderate, and severe atmospheric conditions on the performance of the 650 nm semiconductor laser. Temperature variations were evaluated on the laser output power, with any wavelength changes monitored.

Effect of Humidity: This study investigated how humidity levels affect laser performance. This effect is caused by the absorption properties of atmospheric water vapor, which reduces the intensity of the laser beam and increases scintillation.

Effect of smoke and aerosol particles: Experiments were conducted at specific, precise ranges to measure the attenuation of the laser beam caused by smoke and airborne particles. The primary objective of these tests was to determine the extent of reduced visibility with and without transmitting a message in such atmospheric conditions. **Statistical Analysis:** The results underwent comparative statistical evaluation to ascertain their significance and consistency with prior investigations, assuring conformity with established findings in the current literature.

Results

The laser underwent performance evaluation under multiple environmental conditions both with and without message transmission. The data presented in Table 1 shows how temperature, humidity, smoke concentration and dust density affect the optical power output.

Effects of Temperature: The thermal stability was evaluated within a temperature range of 12°C to 45°C. The optical power decreased from 102.4 μW to 92.8 μW as the temperature increased without message transmission. The power showed a greater decrease from 292.1 μW to 142.3 μW during message transmission which indicates that active signal modulation is more sensitive to thermal changes. The higher initial power output during message transmission could be due to signal amplification yet the major drop indicates that rising temperatures introduce more noise or signal loss.

The Effect of Humidity: The analysis spanned 10% to 99% to duplicate conditions from desert to highly humid environments. The optical power dropped dramatically from 89.7 μW to 14.9 μW when no message transmission occurred which showed major signal degradation in humid air. The initial power reached 314.5 μW during message transmission but dropped dramatically to 13.7 μW when humidity reached its maximum level. The embedded messages enhance the baseline signal power, but they remain highly susceptible to water vapor-induced dispersion effects.

Smoke Concentration: The evaluation of smoke levels from 155 ppm to 580 ppm demonstrated pollution conditions from light to heavy industrial environments. The optical power dropped from 211.7 μW to 12.4 μW when message transmission was absent, but it decreased from 364.2 μW to 9.72 μW when message transmission was present. The signal interference caused by smoke particles becomes more severe because of increased absorption and scattering effects which leads to a greater power decrease. The initial power advantage of message transmission becomes insignificant when smoke concentrations increase because performance levels reach similar states.

Dust Density Effects: The assessment of dust concentrations spanned from 213 mg/m^3 to 714 mg/m^3 to simulate both clean air conditions and environments with dense particulate matter. The optical power decreased substantially from 86.3 μW to 2.9 μW when message transmission was absent, but it decreased from 272.6 μW to 19.8 μW when message transmission was present. The embedded message scenario maintains better power output than the other scenario even though dust affects performance in both cases which indicates improved resistance to dusty conditions. The signal encoding methods seem to reduce scattering losses to some extent which leads to this outcome.

The research shows that embedded message transmission produces higher initial optical power but remains more vulnerable to environmental conditions than idle operation. The signal strength decreases significantly when exposed to temperature and humidity changes, but smoke and dust particles cause complete signal loss at high concentrations. The research demonstrates why adaptive modulation techniques need to be developed for improving laser communication reliability in harsh environments. Future research approaches could focus on these methods of error correction and wavelength adjustment techniques to minimize these adverse effects.

Table 1. Outcomes Associated with 650 nm Semiconductor Laser with Message Transmission and Without Message Transmission.

Condition	Range	Optical Power Without Message (μW)	Optical Power With Message (μW)
Temperature (°C)	12°C to 45°C	102.4 μW to 92.8 μW	292.1 μW to 142.3 μW
Humidity (%)	10% to 99%	89.7 μW to 14.9 μW	314.5 μW to 13.7 μW
Smoke (ppm)	155 ppm to 580 ppm	211.7 μW to 12.4 μW	364.2 μW to 9.72 μW
Dust(mg/m^3)	213 mg/m^3 to 714 mg/m^3	86.3 μW to 2.9 μW	272.6 μW to 19.8 μW

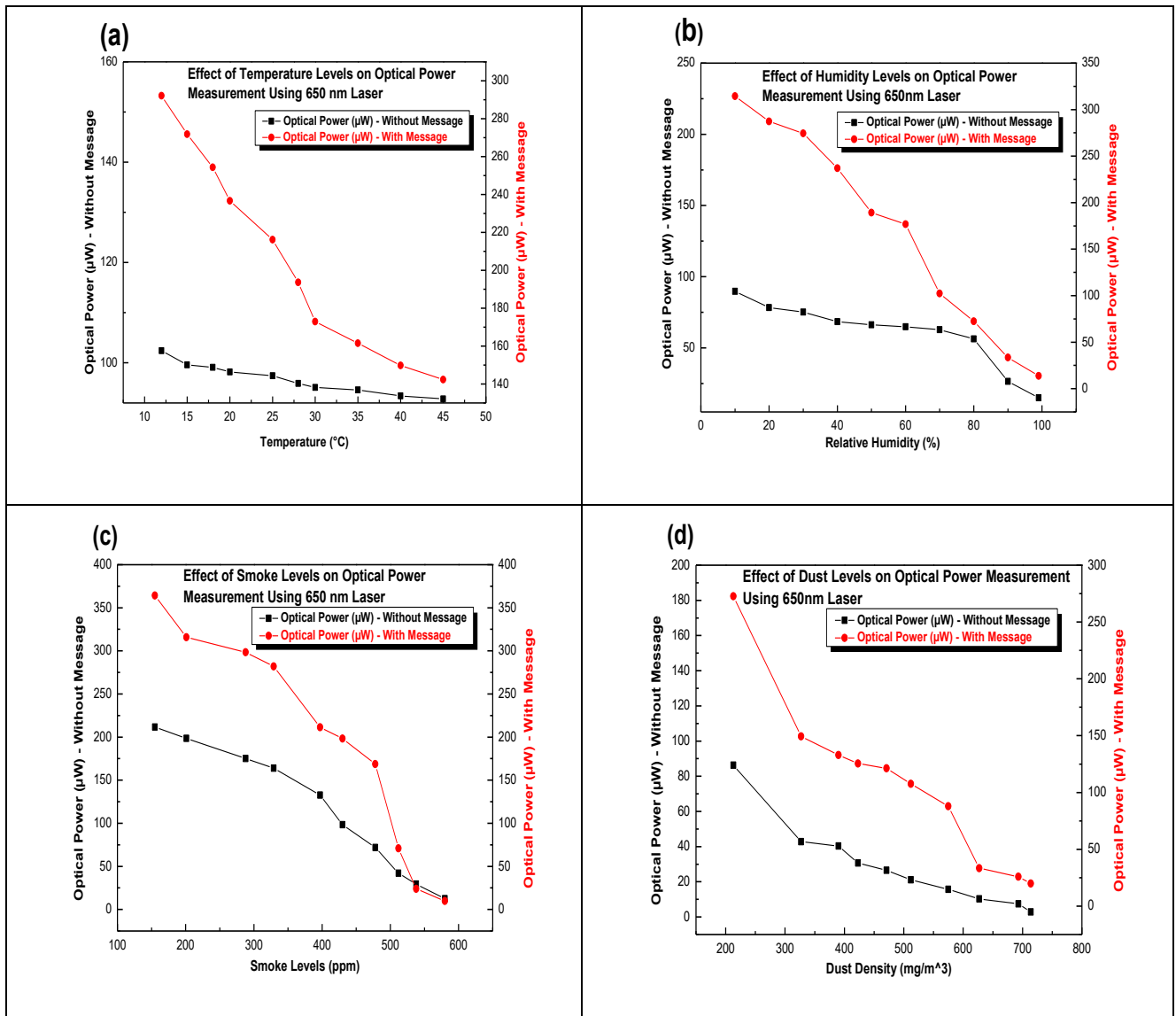


Figure 2. The 650 nm laser performance under different environmental condition.

This study conducted optical power tests on a 650 nm laser with varying environmental figure 2. (a) temperature, (b) humidity, (c) smoke, and (d) dust levels ranging from mild to moderate to extreme. During the experiments, the optical power of the laser decreased in all cases resulting from the attenuation, scattering, and absorption effects. The laser transmission grade “with the message” showed decreasing optical power levels which indicates the environmental factors were degrading the data transmission. The gathered optical power measurements reinforced that the changing temperature affects the performance of the laser system.

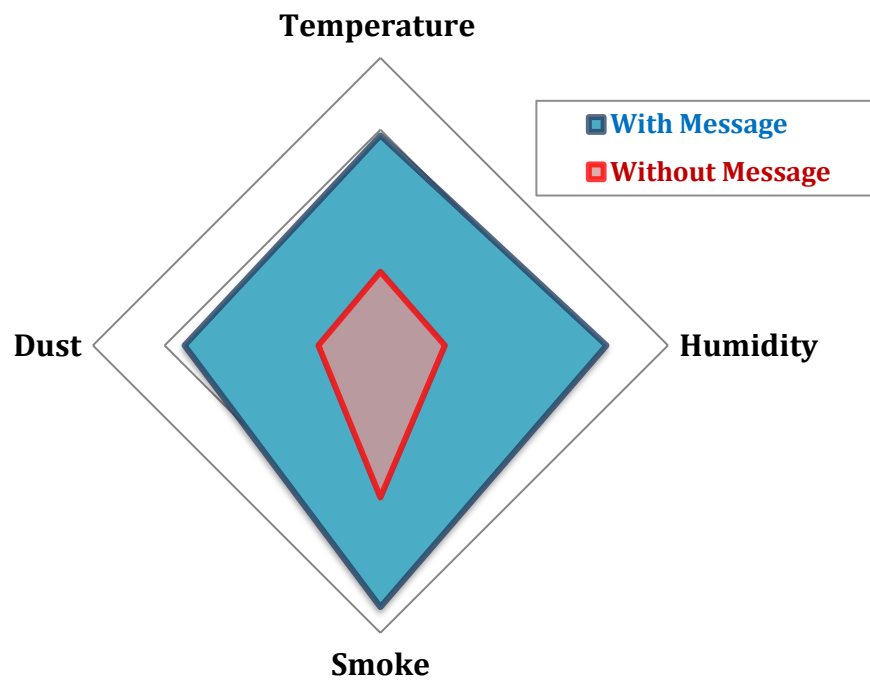


Figure 3. Radar Chart Comparing Average Optical Power Response Under Varying Environmental Conditions.

In Figure 3, the average optical power (OP) from a 650 nm laser is shown under various atmospheric conditions like temperature, humidity, smoke, and dust for two cases with and without message transmission. While the pulsed laser with message transmission performs better overall, it suffers from worse adaptability to continuous environmental changes, particularly humidity and dust. In contrast, the continuous laser with no message transmission performs poorly, but displays more stable operations. This comparison illustrates the trade-off in laser systems between performance effectiveness and the degree of sensitivity to environmental factors.

Calculation of Total Attenuation

This section summarizes the theoretical equations applied to assess the efficiency of an optical wireless communication system in different atmospheric conditions. The system performance metrics were evaluated and calculated based on the total attenuation equation (1). The theoretical and experimental results portray the intricate impacts of atmospheric parameters on the signal transmission in terms of power loss and fading of the laser output signal. The calculated equations generate a number of graphs depicting dependence of attenuation on signal performance for various atmospheric conditions. The discussion focuses on the behavior trends in these graphs to explain the practical impact of atmospheric conditions on laser optical communication systems.

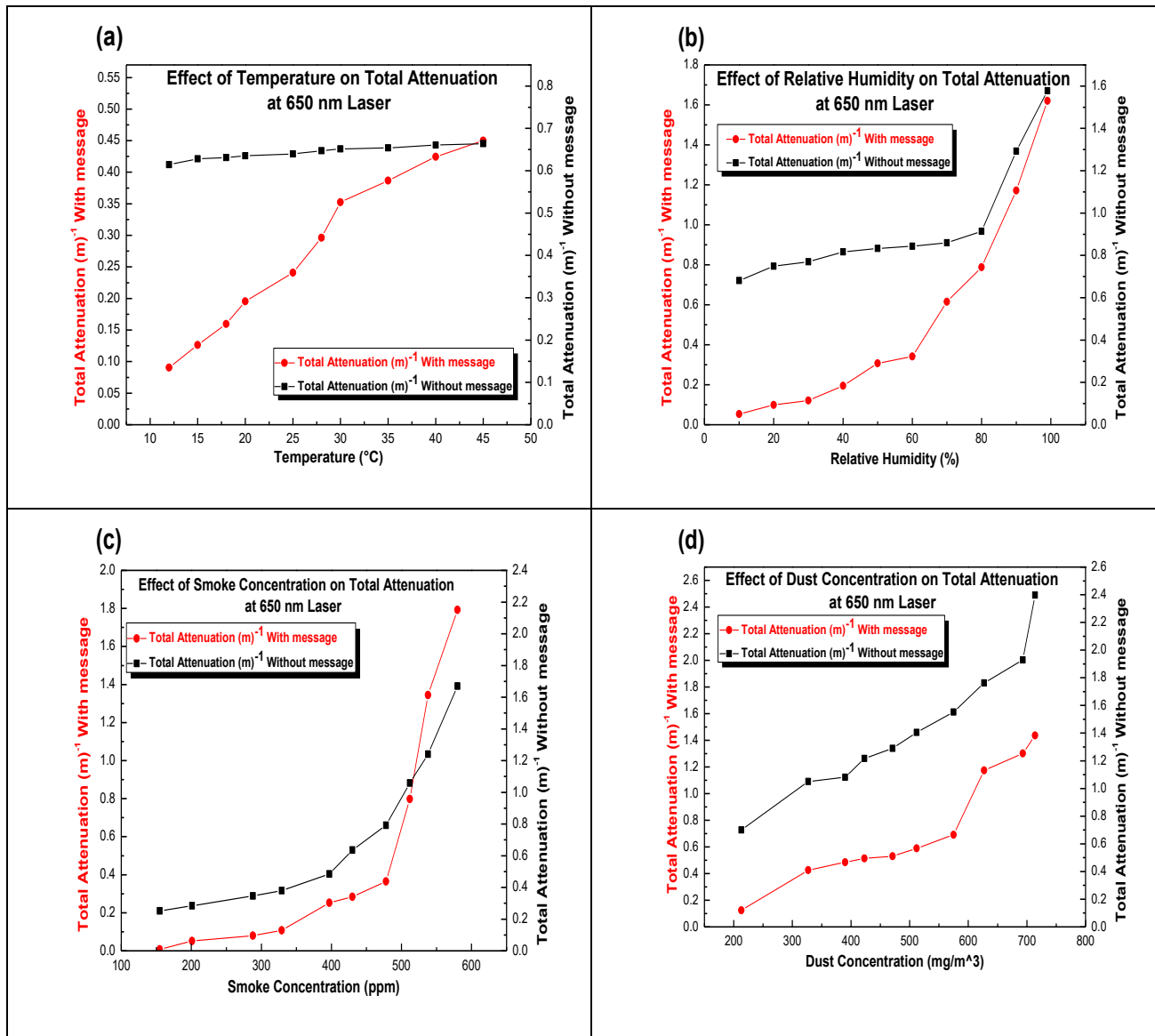


Figure 4. Variation of Total Attenuation Under Different Atmospheric Conditions.

The four line graphs in the figures demonstrate how different environmental factors affect the total attenuation of a 650 nm laser. Figure 4. compares two scenarios with and without message transmission to show how the overall attenuation for a 650 nm laser varies under various air conditions. With only a little variation between the two scenarios, subfigure (a) shows that overall attenuation progressively rises with temperature, suggesting mild thermal impacts on signal loss. Since water vapor significantly increases absorption and scattering, the "with message" situation is particularly sensitive in (b), where relative humidity exhibits a steady attenuation at low levels but rises abruptly at greater humidity. The concentration of smoke in (c) causes a minor increase at low concentrations and a dramatic rise at high concentrations, when fine particles cause significant scattering and cause the modulated signal to degrade more. Although the "without message" example begins with a higher baseline loss, dust concentration gradually raises attenuation for both cases in (d). Overall, the findings emphasize a trade-off between performance and robustness in free-space optical communication systems, demonstrating that although message transmission can function better in milder environments, it is more susceptible to severe atmospheric disturbances.

Calculation of SNR, BER, and Scintillation

To evaluate how different laser wavelengths performed in clarity of the signal over distance, the Signal-to-Noise Ratio of SNR, BER, and Scintillation was examined on the laser transmission range using equations (2) and (3) to calculate SNR and equation (4) for BER.

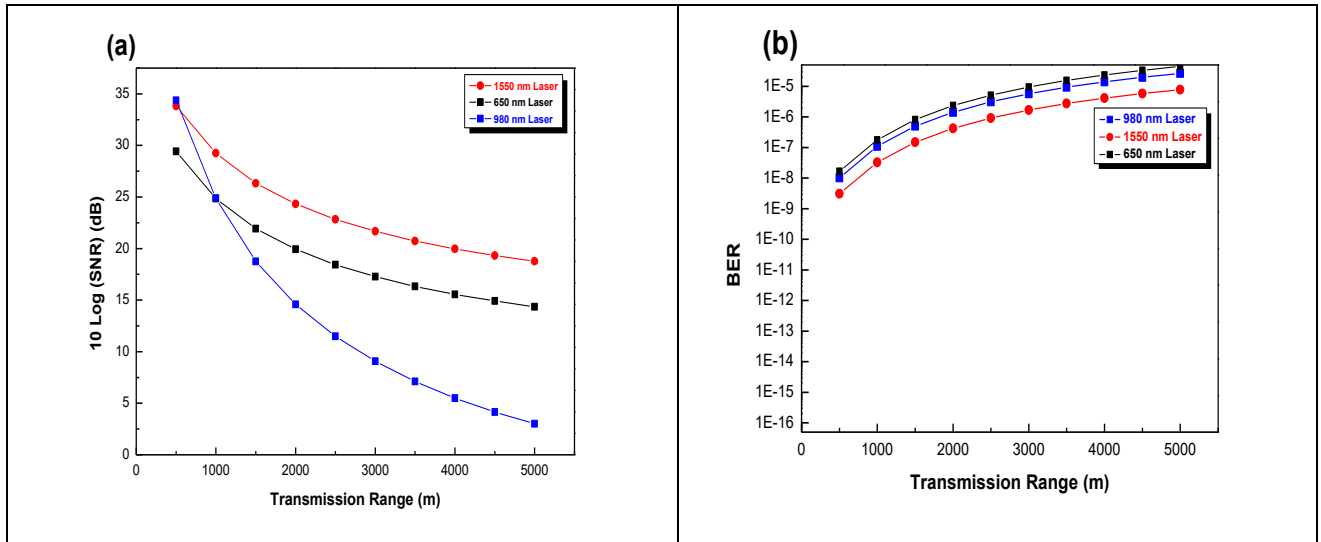


Figure 5. SNR and BER versus Transmission Range for 650 nm, 980 nm, and 1550 nm Lasers.

Figure 5. (a) can be noted that transmission ranges of 650 nm, 980 nm, and 1550 nm lasers have differing SNR ratios. With an increase of transmission range, SNR for all wavelengths decreases which reveals signal deterioration over distance. Out of the three, the 1550 nm laser performs the best overall sustaining the highest SNR while 650nm comes in second and 980 nm exhibits the worst performance. This trend supports the hypothesis on the 1550 nm wavelength, which has better long range FSO due to less atmospheric attenuation and superior propagation characteristics. While figure 5. (b) Bit Error Rate (BER) changes with transmission distance for three different laser wavelengths: 650 nm, 980 nm, and 1550 nm. At distances ranging from 500 m to 5000 m, BER for all three wavelengths shows severe degradation due to increased attenuation and noise, which impacts signal quality. Of the three laser wavelengths, 1550 nm laser demonstrates the lowest BER at all distances evaluated, with 980 nm yielding intermediate results and 650 nm exhibiting the highest BER. This behavior follows their corresponding SNR results and reconfirms the superiority of longer optical wavelengths, particularly 1550 nm, in providing reliable communication over long-range free-space optical links.

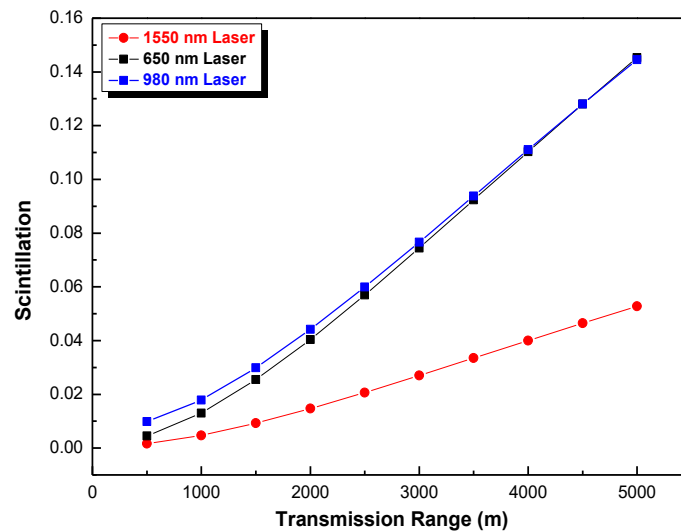


Figure 6. Impact of Propagation Distance on Scintillation Index for 650, 980, and 1550 nm Lasers

The change in the scintillation index calculated by equation (5) concerning the Figure 6. ranges of transmission depict three laser emission lines, specifically at 650 nm, 980 nm, and 1550 nm. The increasing trend of the scintillation index as transmission distance is increased from 500m to 5000m suggests that all three laser emission lines experience atmospheric turbulence stimulated intensity fluctuations. As characterized

earlier, the 980 nm laser shows the highest scintillation values followed by the 650 nm laser and the 1550 nm laser exhibits the lowest scintillation at all ranges. It can therefore be inferred that less than one micron laser wavelength is sensitive to turbulence fluctuation induced by atmospheric conditions where the 1550 nm laser topping the list in performance makes it favorable for long range free space optical communication under turbulent conditions.

Outdoor Environment Results

To assess how a system performs in real-world conditions, the authors of this paper gathered measurement data over a 50 meter link using a 650nm laser. Data was collected at different times of the day namely, 9 AM, 11 AM and 1 PM, and the ambient temperature of the surrounding environment was also noted at 32°C, 35°C and 40°C respectively. Table 2.

Table 2. Outdoor Measurement of 650 nm Laser Received Optical Power Versus Distance and Temperature.

Distance (m) Outdoor 50 meter for 650 nm Laser	Optical Power (mW) 32°C at 9 AM	Optical Power (mW) 35°C at 11 AM	Optical Power (mW) 40°C at 1 PM
5	15.93	12.97	11.76
10	13.27	9.42	11.03
15	11.86	8.11	9.69
20	10.23	6.91	8.74
25	9.02	5.31	6.58
30	7.51	5.07	5.29
35	5.31	4.17	4.06
40	4.67	3.92	3.91
45	4.11	3.05	3.56
50	3.74	2.82	2.18

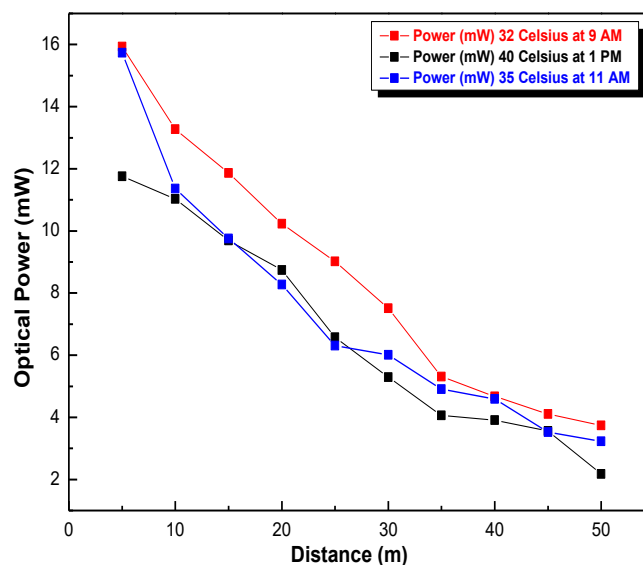


Figure 7. 50 Meter Outdoor Link Optimum Received Optical Power With Varying Temperatures And Times Using 650nm Laser.

Figure 7 illustrates the received optical power while using a 650 nm laser in an outdoor setting (power measurements of optical range lasers in receivers). Measurements were taken at 9 AM (32 degrees), 11 AM (35 degrees), and 1 PM (40 degrees). The results show that there is a drop in power received with increase in distance from the source. This behavior shows the combined impacts of distance-related path loss and factors like temperature and weather conditions which lead to weakening the signal.

Conclusion

The research demonstrates how various environmental elements affect the performance of a 650 nm semiconductor laser particularly when used for data transmission. The experimental data showed that temperature increases from 12°C to 45°C caused optical power to decrease to 92.8 μW without messaging and to 142.3 μW with messaging. The results show that active signal modulation makes the laser system more sensitive to temperature changes, possibly because of additional stress from modulation. The performance of the system decreased substantially due to changes in relative humidity. The optical power decreased from 89.7 μW to 14.9 μW when there was no message and from 314.5 μW to 13.7 μW when there was a message. The main signal transmission obstruction in humid environments results from water vapor absorption and scattering. The presence of smoke and dust particles proved to be the most damaging to the system. The power output dropped to 12.4 μW when smoke concentration reached 580 ppm without message transmission and to 9.72 μW with message transmission. The highest level of significant deterioration occurred at 714 mg/m^3 when dust reduced power output to 2.9 μW and 19.8 μW . The main reason for these losses is the increased scattering and absorption that occurs during the optical transmission process. The study used total attenuation calculations to analyze these effects in each testing condition. The measurements provided quantitative assessments of signal clarity and loss which proved the strong relationship between environmental intensity and system performance degradation. The research reveals major challenges that free-space optical communication (FSO) devices encounter when deployed in operational environments. The study demonstrates that dependable performance under atmospheric variations requires system architectures which combine adaptive modulation with sophisticated error correction and possibly multi-wavelength transmission techniques. Notably, the assessment covered both indoor and outdoor testing environments. Also this conclusion was supported by important SNR, BER, Total Attenuation, and Scintillation metrics.

Future research needs to develop advanced compensation algorithms and conduct extensive field tests to evaluate system performance under different atmospheric stressors which will lead to more reliable FSO communication solutions that can operate effectively in various challenging real-world conditions.

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