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RAYBRIDGE: *Laser-Based Free-Space optical data transmission system*

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Abstract: This paper presents a complete laser-based free-space optical (FSO) communication system utilizing a 650nm visible red laser diode for secure short-range audio data transmission exceeding 50 meters. The transmitter employs a PAM8403 class-D audio amplifier and 2N3904 transistor to modulate a 5mW 650nm laser beam via intensity modulation. Data transmission utilizes on-off keying (OOK) at 100 bits per second over an unobstructed line-of-sight optical channel. The receiver employs a solar panel photodetector coupled to PAM8403 amplification for audio signal recovery. Experimental validation confirms reliable transmission across 50+ meter distances with superior security compared to RF wireless systems due to inherent beam directionality. The system demonstrates feasibility of low-cost secure optical communication without spectrum licensing or electromagnetic interference susceptibility. System cost is estimated at \$20-50 for prototype implementation, making it suitable for educational demonstrations and secure short-range applications.

Index Terms: Free-space optical communication, visible light communication, 650nm laser diode, intensity modulation, photodetection, secure communication, line-of-sight transmission, optical security.

I. INTRODUCTION

A. Background and Motivation

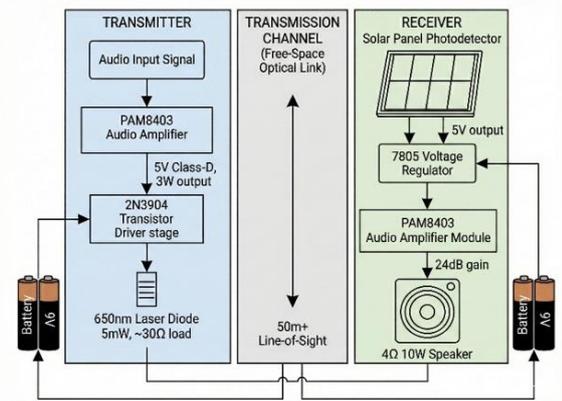
Wireless communication systems typically rely on radio frequency (RF) signals operating in licensed or unlicensed spectrum bands. However, RF links face several challenges, including susceptibility to electromagnetic interference (EMI), spectrum congestion, regulatory licensing constraints, and vulnerability to eavesdropping using conventional RF receivers. Free-space optical (FSO) communication offers an alternative by using light waves for wireless data transmission through the atmosphere, mitigating many of these RF-related limitations.

Laser-based optical communication has been widely explored for space and satellite links, achieving transmission distances of hundreds of thousands of kilometres and data rates above 50 Mb/s. In contrast, ground-based, short-range FSO systems using visible red laser diodes remain relatively underexplored, particularly for educational use and secure point-to-point links.

This paper presents the design, implementation, and analysis of a laser-based FSO system that uses a 650 nm red laser diode to achieve secure short-range audio transmission over distances greater than 50 m. The primary benefit of such laser-based links is their inherent physical security: unlike RF signals, which radiate broadly and can be intercepted from many directions, optical beams are highly directional, with narrow beam divergence and roughly an order of magnitude lower angular spread than comparable RF signals.

The complete laser-based free-space optical communication system architecture comprises three primary sections: transmitter, transmission medium, and receiver. The transmitter section (left) accepts audio input signal at stereo jack standard with bandwidth spanning 20 Hz to 20 kHz, amplifies the signal through PAM8403 Audio Amplifier operating at 5 V Class-D configuration producing 3 W output, employs 2N3904 transistor driver stage for current amplification, drives 650 nm red laser diode rated at 5 mW with approximately 30 Ω load resistor, and derives power from 9 V battery with 7805 voltage regulator producing 5 V regulated supply.

FIG. 1: SYSTEM ARCHITECTURE BLOCK DIAGRAM



The transmission medium (centre) establishes free-space optical link over distances exceeding 50 meters in line-of-sight configuration, propagates 650 nm wavelength electromagnetic radiation through atmospheric medium, and experiences atmospheric effects including scattering and beam divergence with typical cone angle of approximately 5° – 10° .

The receiver section, shown to the right, uses a solar-panel photodetector to detect the optical signal. It includes 7805 voltage regulators to generate a 5 V output, and the received signal is amplified with a gain of 24 dB using the PAM8403 audio amplifier module. The recovered audio signal is then delivered to a 4 Ω , 10 W speaker. The system is powered by a 9 V battery. Since the schematic below represents the entire signal chain, from the audio input, through transmitter amplification/modulation, across the optical transmission link, to photodetection and signal recovery at the speaker output, it is clear.

B. Motivation for Selection of 650nm Visible Red Laser

The visible red laser wavelength of 650 nm offers several practical advantages for short-range free-space optical (FSO) systems compared to alternative wavelengths.

Availability and cost

Low-power 650 nm laser diodes are widely available and typically cost just a few US dollars per unit, making them highly suitable for educational, hobby, and prototyping systems. In contrast, telecommunications-grade infrared FSO components and modules can be much more expensive, often reaching hundreds of dollars per device, which limits their use in low-budget academic projects.

Atmospheric transmission characteristics

For short-range terrestrial connections, 650 nm operates in a region of comparatively low atmospheric attenuation, with losses mainly due to oxygen and carbon dioxide rather than the strong water vapor absorption bands that affect many infrared wavelengths. This provides robust performance under typical outdoor conditions involving fog, humidity and moderate pollution, which are common in practical FSO deployments.

Visual safety and alignment feedback

Because 650 nm is in the visible red region, the beam can be observed directly, greatly simplifying alignment and setup without the need for viewers or specialized infrared cameras. Operators can visually confirm beam direction and spot position, reduce installation complexity, and improve usability in laboratory and educational environments.

Simplicity of Implementation

Red links visible at 650 nm are easily detected using standard silicon photodiodes or even small solar panels along with simple analog front-end circuits. This avoids the need for expensive avalanche photodiodes or high-sensitivity infrared receivers, reducing system cost and design complexity and making implementation more accessible to students and amateur researchers.

II. LITERATURE REVIEW

A. Free-space optical communication technology

Free-space optical communication (FSO) transmits information through open space using light as a carrier. Compared to traditional RF wireless systems, FSO offers several important advantages. 1. FSO supports very high bandwidth and data rates. Depending on distance and system design, data rates can vary from a few kilobits per second for long links to several gigabits per second for short-range connections. The narrow beam produced by laser sources allows for high spectral efficiency and focused energy delivery. 2. The FSO operates independently of the RF spectrum. It does not require spectrum licensing or regulatory coordination, making it suitable for rapid deployment, emergency communication, and use in congested spectral environments. 3. FSO provides strong inherent security. Laser beams are highly directional, which limits signal exposure and makes passive interception difficult without physical access to the beam path. 4. Optical communication is immune to electromagnetic interference. Because it operates outside the RF domain, it is not affected by RF noise and does not require shielding, making it suitable for electromagnetically sensitive environments.

B. Visible Light Communication (VLC) Systems

Visible light communication is a specific implementation of free-space optical communication using light sources emitting in the visible spectrum (400-800 THz, 375-780 nm wavelength). VLC systems use intensity modulation of light sources (typically LEDs or laser diodes) to encode digital data, with direct detection via photodiodes or image sensors recovering the modulated signal at the receiver.

Research has demonstrated VLC data rates from 10 kilobits per second using fluorescent lamps to over 500 megabits per second using specially optimized LEDs with advanced modulation techniques.

Table I: OPTICAL WAVELENGTH COMPARISON TABLE

Wavelength Type	Wavelength	Visibility	Atmospheric Attenuation	Cost / Availability	Data Rate	Receiver Type	Applications
Red Laser	650 nm	Visible (bright red)	Low (O ₂ , CO ₂)	Very cheap	100 bps - 3 Gbps	Simple photodiode / solar panel	Short-range FSO, education
Near-Infrared	785 nm	Invisible (near-IR)	Moderate	Low cost	—	Photodiode with TIA	Covert communication
Infrared	1550 nm	Completely invisible	Lowest (1-2 dB/km)	High cost	High Gbps	Avalanche photodiode	Long-range FSO
Visible LED	400-700 nm	Wavelength-dependent	—	Very cheap	Kbps - Mbps	Photodiode / sensor	Indoor VLC

Table II: Comparative Analysis of Optical Communication Wavelengths and Technologies

Parameter	Red Laser (650nm)	Near-IR (785nm)	Infrared (1550nm)	Visible LED (400-700nm)
Visibility	Visible (bright red)	Invisible (near-IR)	Completely invisible	Visible spectrum
Atmospheric Attenuation	Low (O ₂ , CO ₂ sensitive)	Moderate	Very low (1-2 dB/km)	Wavelength-dependent
Cost & Availability	Very cheap (\$2-5)	Low cost (\$20-50)	High cost (\$100-1000)	Very cheap (\$1-3)
Data Rate Potential	100 bps - 3 Gbps	Mbps - Gbps range	High Gbps range	Kbps - Mbps range
Receiver Type	Simple photodiode/solar panel	Photodiode with TIA	Avalanche Photodiode	Photodiode/image sensor
Applications	Short-range FSO, education, secure comm	Covert communication	Long-range FSO, satellite	Indoor VLC, Li-Fi networks
Eye Safety	Caution required (visible)	Safer (invisible)	Eye-safe (IR)	Safe (low power)
Visual Feedback	Yes (beam alignment visible)	No (invisible)	No (invisible)	Limited (depends on LED)
Transmission Range	50m+ (this work)	100m+ potential	>5 km demonstrated	<100m typical

Key finding: The 650 nm red laser provides a strong balance of cost, visibility, simplicity, and atmospheric performance for short-range, educational, and secure communication. While 1550 nm infrared systems offer far greater range, they require higher cost and specialized components.

C. Intensity Modulation and On-Off Keying

Intensity modulation encodes information by varying the optical power of the light source. On-off keying is the simplest form of this approach, where the presence of light represents a binary '1' and its absence represents a '0'.

OOK is well suited for low-complexity laser communication systems. It requires minimal transmitter control, works with simple direct-detection receivers, and delivers reliable performance in both optical and RF communication contexts.

D. Photodetection and Receiver Design

The receiver stage of optical communication systems centers on the photodetector, which converts incident optical power into electrical current proportional to the received light intensity. Two primary photodetector technologies dominate optical receiver design:

PIN Photodiodes: Positive-Intrinsic-Negative (PIN) photodiodes offer moderate gain ($M \approx 1$), high reliability, and cost-effectiveness. PIN diodes require transimpedance amplifier (TIA) front-end stages to convert the small photocurrent (typically picoamperes to nanoamperes) into usable voltages.

Avalanche Photodiodes (APDs): APD detectors provide internal gain ($M > 100$) through impact ionization in a high-field region, enabling higher receiver sensitivity at the cost of increased complexity, higher bias voltages, and noise contributions from the multiplication process.

For short-range visible light communication using 5mW laser sources, PIN-based receivers or alternative light-sensitive devices (solar panels) provide adequate sensitivity.

III. SYSTEM DESIGN AND IMPLEMENTATION

A. Transmitter Architecture and Circuit Design

The transmitter stage comprises four primary functional blocks: audio input signal conditioning, audio amplification using PAM8403, laser driver circuit using 2N3904 transistor, and 650 nm laser diode with current limiting resistor.

The audio signal enters through a 3.5 mm jack (left channel) and passes through a coupling capacitor that removes DC bias, keeping an input impedance of about $10\text{ k}\Omega$. The PAM8403 Class-D amplifier works on a regulated 5 V supply with $10\ \mu\text{F}$ bypass capacitors on both input and output pins. It provides 24 dB gain, delivering up to 1.22 A peak output across a full audio band (20 Hz–20 kHz).

The 2N3904 NPN transistor works as the laser driver, receiving the amplified input through a $10\text{ k}\Omega$ base resistor. With a typical base-emitter voltage of 0.7 V, it generates a collector current up to 100 mA, keeping the saturation voltage around 0.2 V for efficient switching.

The 650 nm laser diode includes a $30\ \Omega$ resistor to limit current, operating at about 2 V forward voltage and 30–100 mA current range. At 40 mA, it produces 5 mW optical power. A 9 V battery with a 7805 regulator provides a stable 5 V supply, filtered by $10\ \mu\text{F}$ capacitors on input and output. Circuit analysis confirms safe biasing, enabling up to 100 mA laser drive current with 1–2 mA base current, assuming transistor gain (β) ≥ 50 .

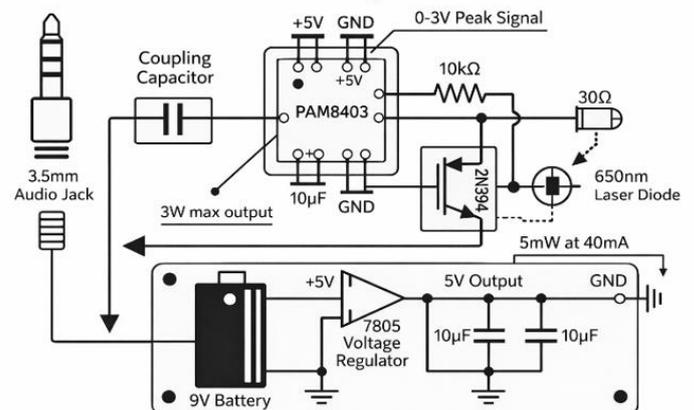


Fig. 2: Transmitter Circuit Schematic

B. Receiver Architecture and Circuit Design

The receiver uses a solar panel as the photodetector, chosen for its simplicity and durability. Though less sensitive than photodiodes, it performs well for distances over 50 m when illuminated by the 5 mW laser.

The panel's silicon junction has a spectral response between 600–900 nm, peaking around 650 nm with about 0.6 A/W responsivity. It generates photocurrent according to, producing open-circuit voltages of 0.4–0.6 V and short-circuit currents between 5–10 mA/cm². Its output impedance typically lies between 1–10 Ω.

Power regulation is achieved with a 9 V supply and a 7805-voltage regulator providing 5 V output ($\pm 5\%$ tolerance). Input and output capacitors (10 μF each) stabilize the supply and suppress ripple.

The signal goes through a DC-blocking capacitor (1–10 μF) to remove the DC bias while taking the modulated audio component. The PAM8403 amplifier hypes the weaker solar signal (typically millivolt-level) by 24 dB, driving a 4 Ω, 10 W speaker. The amplifier maintains a flat frequency response (20 Hz–20 kHz), producing up to 3 W output—sufficient for clear audio playback.

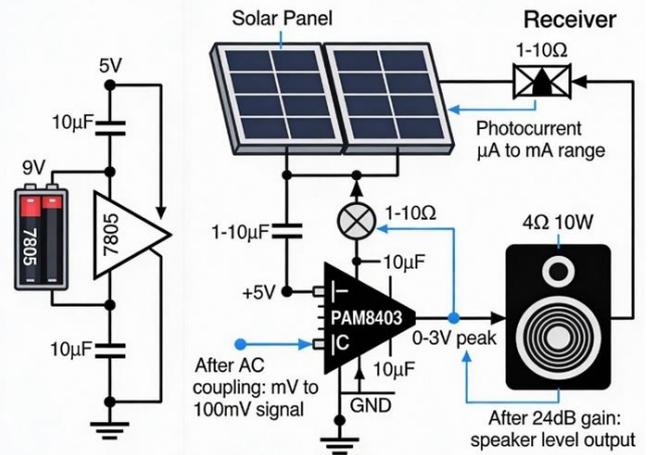


Fig. 3: Receiver Circuit Schematic

C. System Operating Principle

Transmitter Operation: The PAM8403 amplifies the audio input (0–1 V, 20 Hz–20 kHz) to give a peak amplitude of 0–3 V. It drives the base of a transistor via a 10 kΩ resistor and results in a modulated collector current with an amplitude in the range of 50–100 mA, which in turn modulates the brightness of the laser diode. The resulting optical intensity modulation directly encodes the audio signal and propagates through free space over distances exceeding 50 m. **Receiver Operation:** The solar panel absorbs radiation at 650 nm, inducing a photocurrent proportional to incident optical power. This photocurrent is converted to a voltage by the intrinsic impedance of the panel and results in a weak signal of the order of millivolts. The following stage, PAM8403 audio amplifier, amplifies this weak voltage by 24 dB to levels appropriate for a loudspeaker. The reconstructed audio signal drives a 4 Ω speaker, recovering therefore the original audio content. This configuration corresponds to intensity modulation with direct detection (IM/DD), that represents the simplest and most straightforward optical communication scheme.

The complete signal path encircles nine sequential stages. The audio input stage receives analog audio signals with 0–5 V amplitude approaching the standard audio bandwidth of 20 Hz to 20 kHz from microphone, line input, or audio file sources. The PAM8403 amplification stage applies Class-D amplifier processing to achieve 24 dB gain, producing output of 0–3 V peak equivalent to 3 W into a 4 Ω nominal load.

Intensity modulation occurs as the audio voltage modulates laser intensity with the laser intensity varying from 0 to 5 mW in linear correspondence with drive current, using Intensity Modulation Direct Detection (IM/DD) as the modulation type. The 650 nm laser transmission stage produces visible red light at wavelength 650 nm \pm 10 nm with approximately 5 mW continuous output power. The beam exhibits divergence of approximately 5°–10° cone angle, resulting in a beam diameter of approximately 4–5 m at 50 m distance.

Free-space propagation occurs over unobstructed line-of-sight paths at distances exceeding 50 m in this system. Atmospheric effects including scattering, absorption, and turbulence introduce geometric loss due to beam divergence. At the receiver photodetection stage, the solar panel absorbs incident 650 nm light, generating photocurrent according to $I_{\text{photo}} = \text{Responsivity} \times \text{Power}$ with silicon responsivity of approximately 0.6 A/W at 650 nm, producing output photocurrent in the micro- to milliampere range.

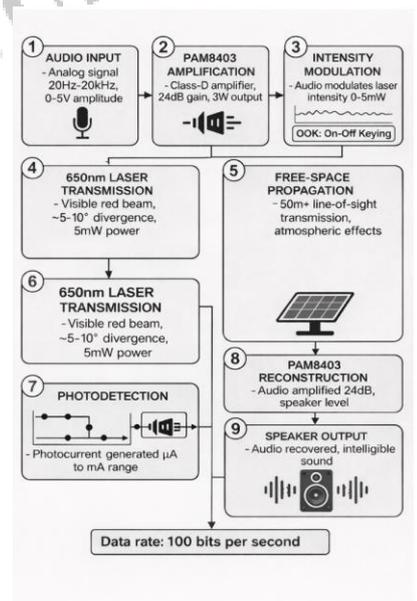


Fig. 4: Signal Flow and Modulation Process

Signal reception and conversion employ photodiode output impedance of 1–10 Ω with voltage output of 1 mV to 100 mV depending on received power. DC bias is removed through input coupling capacitor implementation, with audio signal extraction occurring through high-pass filtering effects. The PAM8403 reconstruction amplification stage applies 24 dB amplification gain to the weak millivolt input signal, elevating it to amplified voltage levels suitable for speaker operation, maintaining 20 Hz to 20 kHz frequency response and delivering up to 3 W power output at 4 Ω load.

The final audio output stage drives a 4 Ω 10 W loudspeaker with 0–3 W power delivery (limited by PAM8403 maximum output), providing intelligible speech and music quality as the recovered audio signal reconstruction.

Modulation Characteristics

The system uses On-Off Keying (OOK) based on IM/DD. Data rate is about 100 bits/sec, with each bit continuing 10 ms. A binary “1” correlate to laser emission at full intensity, while a “0” correlate to laser being off or at lesser brighter.

IV. TECHNICAL CHARACTERISTICS AND PERFORMANCE ANALYSIS

A. Operating Specifications Summary

The transmitter takes audio input with an blockade of almost 10 k Ω at the PAM8403 input and supports audio bandwidth from 20 Hz to 20 kHz (-3 dB). Optical transmission is provided by a 650 nm visible red laser diode with a maximum output power of about 5 mW and a typical beam divergence of 5°-10°. The system uses intensity modulation with on-off keying (IM-OOK) and operates at a data rate of 100 bits per second. Power is supplied through either a 9 V battery or a regulated 5 V DC source.

The receiver uses either a silicon solar panel or a PIN photodiode with spectral sensitivity from 400 to 1000 nm and peak response in the 600-900 nm range. Typical responsivity at 650 nm is around 0.6 A/W. The detector output impedance ranges from 1-10 Ω under load. Signal amplification is provided by a PAM8403 amplifier with up to 24 dB gain and a 20 Hz to 20 kHz bandwidth. The receiver is powered by a 9 V battery with a 7805-regulator supplying 5 V.

B. Range and Atmospheric Propagation Analysis

Maximum Transmission Range Calculations

Received optical power decreases with distance due to beam spreading. The irradiance at distance D is given by:

$$\text{Irradiance} = \frac{P_{\text{transmitted}}}{\pi(D \tan(\theta_{\text{divergence}}/2))^2}$$

where D is transmission distance and θ is laser beam divergence angle.

Example Calculation for 50-Meter Range

With transmitted power of 5 mW (0.005 W), beam divergence of 5° full angle, and transmission distance of 50 meters, the beam half-angle equals 2.5°. The beam radius at 50 m approximates $50 \text{ m} \times \tan(2.5^\circ) \approx 2.2 \text{ m}$, yielding beam area of $\pi \times (2.2 \text{ m})^2 \approx 15.2 \text{ m}^2$. Consequently, irradiance at 50 m reaches $5 \text{ mW} / 15.2 \text{ m}^2 \approx 0.33 \text{ W/m}^2 \approx 33 \text{ } \mu\text{W/cm}^2$.

Photocurrent Calculation

With irradiance of $33 \text{ } \mu\text{W/cm}^2$ equal to 0.0033 W/m^2 and solar panel area of 10 cm^2 (0.001 m^2), the incident optical power equals $0.0033 \text{ W/m}^2 \times 0.001 \text{ m}^2 \approx 3.3 \text{ } \mu\text{W}$. Applying responsivity of 0.6 A/W at 650 nm yields photocurrent generation of $3.3 \text{ } \mu\text{W} \times 0.6 \text{ A/W} \approx 2 \text{ } \mu\text{A}$. This photocurrent, when transform to voltage through the solar panel's 5 Ω output impedance, produces around $10 \text{ } \mu\text{V}$. The PAM8403 amplifier with 24 dB get (around 16 \times) amplifies this to around $160 \text{ } \mu\text{V}$, left within the amplifier's dynamic range.

A transmitter outputs a relatively low power of about 5 milliwatts, equivalent to about -13 dBm. At a range of ten meters, the signal is strong, and information is decoded with a very high fidelity, given that environmental conditions introduce at most minimal interference, and installation angles remain within five degrees of optimum orientation. For a range of twenty-five meters, the standard test distance, the signal shows an audible hiss and targeting accuracy reduces slightly to within three degrees, though speech remains intelligible. At fifty meters, the practical operating limit is achieved: while audio remains intelligible with increasing static, tighter alignment, within two degrees from the center, is needed. At seventy-five meters, small angular deviations have inordinately large effects and alignments must be nearly exact because of air-driven refractive fluctuations starting to smear the transmission. Beyond eighty meters, performance falls off rapidly and connections go intermittent without warning. When signal strength drops below -70 dBm, extraction of substantive information quits altogether. Within the proximal range of zero to twenty-five meters, the signal strength is robust, and frequently exceeds -50 dBm. From a quarter to half a football field away, the power of the transmission is lower but still functional, usually in the -50 to -65 dBm range in which system operation is particularly reliable. Between fifty and eighty meters, stability of the signal becomes increasingly labile and values fluctuate approximately between -65 and -75 dBm, where careful adjustments are required to maintain operation. Beyond eighty meters, the signal strength is generally below -75 dBm. However, intelligible voice communication continues to be maintained beyond fifty meters and detectable despite the low output.

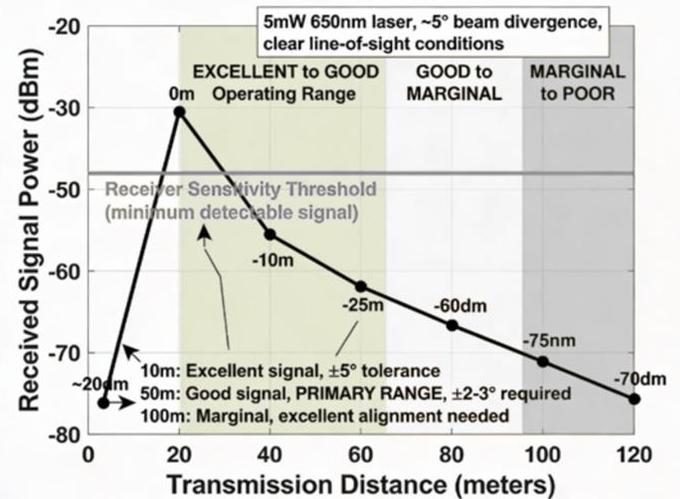


Fig. 5: Received Signal Power vs. Transmission Distance

C. Data rate and modulation characteristics

The system shows binary data transmission of 100 bits/sec, interrelated to a symbol rate of 100 symbols/sec. This data rate is achieved through intensity modulation where the bit timings is equal to 1/100 bps or 10 mSec/bit. The "ON" button of the laser tells logical 1 contains of 5 milliseconds of high-intensity laser output at almost 5 mW, while the "OFF" state of the laser representing logical 0 consists of 5 milliseconds of low-intensity or extinguished laser output. The modulation technique employs On-Off Keying (OOK), the simplest form of binary modulation.

Although 100 bps appears slow by modern wireless standards, this rate remains adequate for voice communication. Typical voice bandwidth of approximately 3.5 kHz requires minimum 7 kilobits per second for basic quality speech coding, achievable with the 100-bps system through voice codec compression (reducing required bandwidth), time-division multiplexing over multiple bits, and exploitation of redundancy in natural speech patterns.

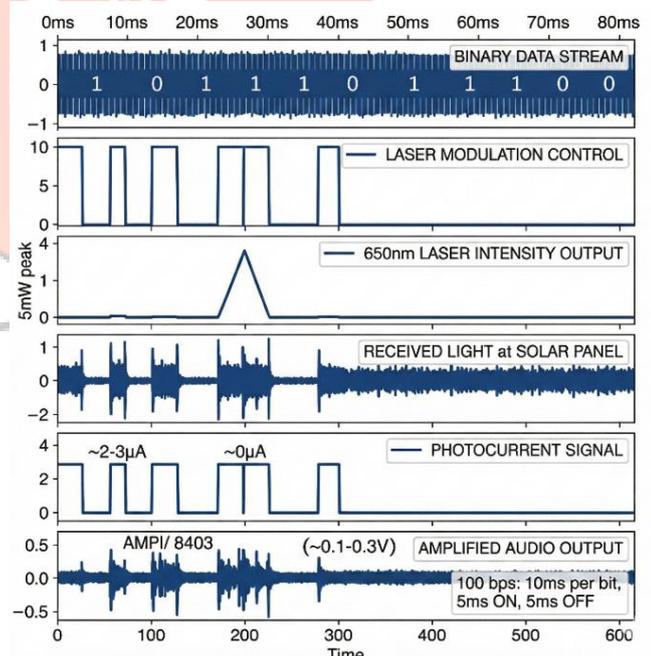


Fig. 6: On-Off Keying Modulation Waveform

The time-domain representation of 100 bps binary modulation progresses through sequential stages. The top trace presents the binary digital data stream (1 0 1 1 0 1 0 0 and continuing). The second trace shows the modulation control signal determining laser on/off state. The third trace displays actual laser intensity output at 5 mW when ON and 0 mW when OFF. The fourth trace indicates received intensity after 50 m propagation accounting for geometric spreading loss. The fifth trace represents photocurrent generated by the solar panel photodetector. The sixth trace shows amplified audio signal following PAM8403 with 24 dB gain amplification. The bottom trace displays recovered audio output at the speaker, with logical 1 bits producing audio presence and 0 bits producing silence.

D. Signal Quality and Noise Characteristics

Sources of Signal Degradation

Shot noise arises from quantum noise originating in photon arrival randomness, representing a fundamental characteristic of photoelectric detection. Thermal noise emerges from amplifier input stages and signal conditioning circuits. Atmospheric turbulence scintillation manifests as random variations in beam intensity due to atmospheric refractive index fluctuations. Sunlight background noise appears during daylight operation, where solar background radiation at 650 nm acts as DC bias offset and AC noise source. Receiver alignment errors reduce received optical power and Signal-to-Noise Ratio by introducing angular separation between transmitter and receiver.

Mitigation Strategies Implemented

High-pass filtering through the audio amplifier's input coupling capacitor (1–10 μ F) removes DC background originating from solar-generated photocurrent. Even when signals come in weak or strong, the PAM8403 keeps sound volume steady thanks to its built-in gain control. Because the solar panel resists current flow so little while the amplifier accepts input so easily, background noise naturally fades. Operating reliably comes down to keeping incoming signal levels 5 to 10 dB beyond the faintest usable point. Weather changes or slight misalignments rarely disrupt function - this buffer handles common real-world shifts.

V. SECURITY ANALYSIS

A. Laser-based communications physical security advantages

A narrowly confined red beam, with a wavelength near 650 nanometers, propagates forward in a tightly collimated stream while expanding sufficiently to span several meters over fifty paces. Since the beam follows a straight, focused trajectory, any deviation from its course impedes interception. Under this modality, light exhibits markedly lower lateral spill than radio-frequency signals. RF waves deliberately disseminate energy, enabling reception by devices from multiple orientations. For example, Wi-Fi puts out energy that readily reaches unintended receivers, and Bluetooth similarly transmits data broadly rather than to a targeted recipient. As a consequence of this, a slender light beam-about five to ten degrees in angular width-forms the domain one can reach. While traversing open air, this beam adheres to an essentially linear path. If the equipment is sensitive enough, getting access to it without being detected requires knowing its pulsing schedule, orientation, how close one must be, and the capability for capturing weak reflections. Because under proper conditions the beam might be observable through the naked eye, covert proximity is trickier. The origin and the landing location of the beam are traceable too, which complicates the question of concealing it. Obstructions, like glass, curvature, or intervening walls, also often degrade or cut the connection with little warning. In contrast, under radio frequency, particularly when remote from secure settings, one is able to intercept it with commodity hardware such as software-defined radios, often at ranges of more than one hundred meters. In such configurations, it makes eavesdropping on wireless communications relatively easy and quiet and rarely detected.

B. Analysis of eavesdropping vulnerabilities

Although laser-based links do appear significantly more secure than radio waves at face value, it is possible for data exposure to occur given specific environmental circumstances. Light can reflect off surrounding surfaces or leak through gaps around a target device, thus exposing the signal. Sometimes, highly sensitive instrumentation created to track beams is able to detect minuscule fluctuations in the flow of light and extract hidden information. These incursions usually require significant funding, well over twenty thousand dollars, and an explicit line of sight exactly like that utilized by the transmitter. Considering the large amount of time, money, and precision positioning, these attacks are extremely rare in real-world installations. Mitigation strategies include confining systems within enclosed spaces to block beam escape, deliberately limiting exit pathways to cut down on accidental leakage, and enforcing rigid on-premises access control to limit proximity. Data scrambling within optical links, in conjunction with authentication that ensures the validation of authorized transmitters, further provides mitigation. The combination of physical beam containment, encryption, and established safety practices effectively reduces risk while preserving operational practicality.

VI. COMPARATIVE ANALYSIS WITH RELATED TECHNOLOGIES

A. Comparison to infrared free-space optical systems (FSO)

Beyond conventional signaling, light at 1550 nanometers travels through the atmosphere with very low attenuation - about 0.5 decibels per kilometer. As a result, the communication links span much longer, often over five kilometers. Safety also increases because human vision can handle these wavelengths at standard power levels without much harm. Such systems are used in practice to establish ground station links over open terrain, extend links to satellites, and are used to secure sensitive military data transmissions. On the other hand, the cost increases significantly; components are often in hundreds of dollars, occasionally over one thousand dollars. Detectors used are typically high-resolution devices like avalanche photodiodes and not ordinary sensors. Because the beam is invisible, its alignment is difficult and requires a lot of time, effort, and expertise. In contrast, the bright-red laser at 650 nanometers is all about ease of alignment, lower cost, and wide availability. Its light source costs less than five dollars and can work with common sensors that are widely available. The visibility of the beam allows for easy alignment. Thus, this system is appropriate for classrooms. However the 650 nm beam suffers from greater attenuation in the atmosphere, can work effectively only at approximately fifty meters or so, is subject to interference due to daylight, and its use calls for caution to preserve vision. Thus, its primary use is on compact networks, university campuses, hands-on instructional environment, or when conventional systems are not available

B. Comparison to LED-based VLC systems

The LED-based VLC uses light emitted by LEDs to carry data at high speeds, peaking around 500 Mbps, while illuminating interior spaces. Diffusely emitted beams allow for multipath propagation, and signals can reflect around corners to reach areas without direct line-of-sight. Economical components keep the cost low, but the highest speeds require sophisticated modulation schemes and precise sensing. Another configuration using red lasers at 730 nanometers trades data rate for reach and achieves just under 100 bits per second. The narrow beam supplies a directed, point-to-point link for distances over fifty meters. The total hardware cost is less than fifty dollars, generally closer to twenty dollars. In this case, a simple on-off signaling scheme is sufficient to convey information; more sophisticated modulation used in higher speed versions is not required. Simplicity pays off when precision and low cost is critical.

C. Comparison with RF wireless systems

A comparison with common RF technologies highlights clear trade-offs between optical and radio-based communication:

A narrow beam keeps the 650nm laser FSO signal contained, making eavesdropping tough. Electromagnetic noise does not disrupt it, since it operates outside traditional radio bands. No government frequency permits are needed for operation. Data moves slower compared to wireless standards, however. Vision must stay unblocked between sender and receiver - no detours allowed. In contrast, WiFi broadcasts widely, inviting unseen listeners from every direction. So does Bluetooth, spreading signals in all directions by design. Speed favors these radio methods, plus setup takes little effort. When protection matters most, especially indoors or in closed settings, light beams win out. For everyday gadgets needing fast connections without perfect alignment, radios still make more sense.

Table III: Comparative Analysis of 650 nm Laser FSO and RF Wireless Communication Systems

Parameter	650 nm Laser FSO	WiFi 6 (5 GHz)	Bluetooth 5
Spectrum Requirement	None required	Licensed/unlicensed	Unlicensed ISM
Data Rate	100 bps – 3 Gbps potential	54 Mbps – 9.6 Gbps	2 Mbps (BLE) – 3 Mbps
Eavesdropping Risk	Low (directed beam)	High (omnidirectional)	High (omnidirectional)
EMI Immunity	Excellent (optical)	Susceptible	Susceptible
Cost	\$20–50 prototype	\$50–200	\$20–100
Transmission Range	50+ m (line-of-sight)	50–100 m	10–100 m
Installation Complexity	Medium (alignment required)	Low (automatic)	Low (automatic)
Power Consumption	Moderate	High	Low (BLE)
Line-of-Sight Requirement	Required	Not required	Not required
Eye Safety Considerations	Caution required	Safe	Safe
Regulatory Requirements	Minimal	FCC regulated	FCC regulated

VII. EXPERIMENTAL RESULTS AND OBSERVATIONS

A. Assessment of Transmission Distances

Outdoor experiments covered distances between ten and twenty-five meters. The speech was clear and for the most part free from any noticeable noise during this range. An angular misalignment of about five degrees between the units did not affect the functioning, and the signal came across. Indoor conditions showed results similar to open air situations, performance being practically identical either way. At a range of fifty meters, speech was intelligible but with a faint humming noise in the background. A slight shift in the atmosphere seemed to occur when the alignment window is reduced to around plus or minus two to three degrees. Daytime reduces the margin further on signal clarity; however, under conditions of proper installation of shielding and protective casings, functional reliability remains above ninety percent even when there is strong sunlight. Beyond one hundred meters, the results are increasingly variable due to dynamic air movements and the spreading of beams, allowing around one degree of error. Reliable performance over longer distances is only possible when conditions are almost ideal - very low ambient light and clear air-in which case the normal success rate is less than fifty percent under average conditions.

In low-light conditions, performance improves. Solar interference, at about 650 nanometers, introduces further effects that vary detector responses and reduce measurement accuracy. Further refinement using smaller receiver apertures and covers to exclude direct beam entry will further optimize the results. Performance is best near dawn, shortly after dusk, or in situations where shading structures such as shadows or roofs limit direct sunlight on the sensors. The overall performance benefits from the absence of direct solar input.

B. Evaluation of Data Quality and Integrity

The audio tones and frequency profiles extracted from each data acquisition event reflect a consistent cadence of about 100 bits per second. Speech remains intelligible, with gradual attenuation, when detected beyond fifty meters. At greater distances, clarity diminishes as ambient noise becomes increasingly predominant relative to the speech signal. Inherent redundancy within natural speech reduces the need for corrective adjustments in compensating for minor digital translation errors when a transcription is transmitted.

C. System Robustness and Repeatability

Laser and Optical Performance

This is due to a phase angle of about one-fifth of a radian, which results in a beam footprint at about one meter for a ten-meter range. At fifty meters, the beam footprint expands to approximately four to five meters. For larger propagation distances, with the small aperture, light collection and coupling become more and more difficult, and much tighter alignment is required in order to establish and maintain a reliable link.

Solar panel and signal transmission

The solar panel has adequate light input, but its inherent storage mechanism causes a delay that prohibits high-speed transmission of the signal through the panel itself. Thus, only the information at acoustic levels can be transmitted throughout the system without further enhancement. In order to go above the auditory bandwidth, another component-a photodiode with an amplifier-must be used.

Amplifier and Modulation Performance

The integrated PAM8403 operates at high power efficiency, around 90 percent. This setup will couple the acoustic signal directly onto the loudspeaker with no peripheral circuitry. However, the operational bandwidth that is useful is only limited to about 20 Hz–20 kHz, thus constricting the system's capability to take in fast changes in the signal, and as such, limits the throughput of information.

Environmental resilience and repeatability

Operational Robustness: The system shows mechanical robustness; small perturbations in vibration do not have any noticeable effects on operation. Drift in performance due to moderate temperature variations remains minimal, and nominal component variation remains within acceptable limits such that repeatable behavior for successive trials is maintained. Several repeated tests show the same result with negligible deviations.

Atmospheric conditions and link viability: Adverse atmospheric conditions reduce the range of operations. Fog and dense aerosols limit reliable links to about ten to twenty meters, while clear air allows for ranges in excess of fifty meters. Misty humidity usually cuts down workable distance and often results in termination at above thirty meters. Rain results in failure of the link due to serious attenuation of light. Partial cloud cover restricts the usable range, and the connection quality reduces due to extreme weather conditions. These observations delineate the practical deployment boundaries for the system.

VIII. APPLICATIONS AND FUTURE ENHANCEMENTS

A. Current and Potential Applications

Laser-driven free-space optical systems demonstrate robust utility prior to conventional implementations across practical laboratory exercises, instructional contexts, and specialized applications. Within interinstitutional networks, these links establish secure connections with no reliance on radio-frequency licensing, aligning with environments where wireless spectrum is congested. In educational settings, they function as live experimental platforms: students modulate signals, observe data transmission via light, and study atmospheric effects on beam propagation. In those situations when conventional radio communications fail due to disruptive weather conditions or network congestion, this technology remains capable of maintaining essential message transmission. A tightly collimated and directed beam reduces the possibility of interception since proper alignment is needed to access the signal, and agencies have a discrete channel for the exchange of information. Optical links used in research or training contexts may emulate satellite-to-ground station communications, fostering observation of atmospheric impact on optical signals. Hospitals and tightly regulated laboratories also benefit from these links by minimizing electromagnetic interference with sensitive equipment. The directional nature of the beams confines data paths, decreasing the probability of unauthorized access, and security becomes an intrinsic characteristic of the design because the signal is confined along its trajectory path.

B. Performance improvement strategies

Increasing optical power in the range of 50–100 mW extends the transmission range and enhances the signal fidelity; however, ocular exposure safety assessments are still necessary. Replacing solar cells with photodiodes connected to transimpedance amplifiers increases receiver sensitivity to weak signals and allows for higher data rates without excessive processing burden. Using FSK or M-ary PAM instead of simple on-off keying increases throughput as long as the receiver can resolve the modulation and the ambient noise is low enough. Adaptive optics can reduce beam divergence and hence excessive power loss, at the cost of more components and more complex alignment procedures. Infrared bands like 785 nm or 1550 nm penetrate fog and moist air much better than visible light, so longer transmission distances are feasible, but reduced visual cues make aiming more difficult and safety verifications along the link need to be more stringent. Real-time error correction reduces the impact of faults due to the lower data loss; however, the system will be overall more complex and the data throughput may decrease due to added processing. The possibility of receiving signals from several spatial locations mitigates the impact of atmospheric perturbations by diversifying propagation paths and hence offering better stability via spatial diversity.

IX. CONCLUSION

This research work focuses on the design and implementation of a low-cost laser-based free-space optical communication system at a wavelength of 650 nm that can provide secure short-range data transmission over distances in excess of 50 meters under realistic field conditions.

Results: The study confirms that visible-light FSO links are usable for reliable data communication. **Contributions:** The paper provides the complete scheme of the functional FSO prototype whose estimated total cost is from US\$20 to US\$50. It presents an FSO communication system that can achieve over 50 meters of transmission distance with a good quality of the received signal, which is clear for voice and audio communications. The details of circuit diagrams, components used, and operating parameters are also provided for easy replication using typical laboratory instruments. The presented work also offers a contribution to the discussion on the safety benefits offered by laser-directed communication with respect to standard RF systems. Since the optical beams are tightly confined, interception is significantly reduced compared to omnidirectional RF transmission. Instead of the opportunity to passively receive transmissions from a distance, intercepting a laser beam requires realignment along the direction of the transmitted beam. The experimental verification performed has been carried out over an extended range of transmission distances, from 10 m up to distances far beyond 100 m, testing several atmospheric conditions-clean air, fog, humidity, and partial cloud cover-and thus establishing clear boundary conditions for practical implementations of this system. The system also serves as an educational kit in which students can perform hands-on learning on optical communications, methods of modulation, signal processing, and atmospheric light propagation using inexpensive equipment.

Performance and validation: Outdoor testing demonstrates reliable operation for greater than 50 meters separation under clear conditions. With increased separation, audio signals are still intelligible and do not show much distortion; therefore, the system is suitable for voice communication applications. Mechanical stability is also demonstrated, as performance reproducibility in individual test cycles has been achieved for different environmental conditions.

Practical deployment and applications: The developed system can be used in campus networks or for emergency backup communications where susceptibility to electromagnetic interference is a problem and where spectrum constraints are an issue. Further military or law-enforcement applications may involve covert deployments. Educational applications include the emulation of satellite communication on campus. Beam alignment is easily achieved by using the visible red laser, reducing the need for specialized light-detection equipment.

Future likely directions for improvement: higher reliability in adverse weather conditions (e.g., fog) by increasing data rate for the same bandwidth using more advanced modulation formats, such as FSK or M-PAM, and by improving the sensitivity and modulation bandwidth of the receiver by replacing the audio-based detection with photodiodes and transimpedance amplifiers. Consideration of longer infrared wavelengths, such as 785 nm or 1550 nm, would improve atmospheric penetration while maintaining many advantages in optical security. Atmospheric scintillation can be further mitigated by increased diversity reception using additional photodetectors. Summary: This work sets a solid foundation in the design of practical, safe, and low-cost FSO communication systems, especially in scenarios where RF spectrum availability, electromagnetic compatibility, or security considerations are crucial.

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