Digital Transmission in Free Space through a High-Power Laser

Alexander Simmons, Curtiss Kane, Ivan Huang, Monica Castro-Suarez

Department of Electrical and Computer Engineering, University of Central Florida, Orlando, FL, 32816

***Abstract* — This project presents the design, implementation, and validation of a free-space optical communication system using a high-power laser and a photodiode receiver. Binary data is modulated via a laser beam, transmitted through open air, detected with a photodiode and transimpedance amplifier, and decoded on a microcontroller to display on an LCD. Successful reception of binary messages was demonstrated over short-range tests in controlled environments.**

***Index Terms* — Free-space optical communication, lasers, photodiodes, amplifiers, microcontrollers, and optical modulation.**

I. INTRODUCTION

A. Background and Motivation

The electric telegraph and wireless telegraphy in the 19th and 20th centuries laid the foundations for electrical long-distance communications. The introduction of lasers and optical fiber technology in the 1950s and beyond were built on these foundations and brought optics and photonics on the forefront of modern telecommunications.

This project aims to use a laser as a digital transmitter to transmit data over free space. In the real world, free-space optical (FSO) communications are currently limited to satellite communications. However, there are no terrestrial applications for FSO communications, and this is the void this project will fill.

B. Relevance and Real-World applications.

Digital technology, optical engineering, and the Internet were vital in the acceleration of research and development in telecommunications and enabled instantaneous communication between people all over the world.

However, there is still a section of telecommunications users that do not rely exclusively on the Internet, especially when they operate in remote areas without Internet access. Amateur radio operators utilize transceivers and antennas to bounce radio waves off the ionosphere for distant communications. Emergency operators utilize the same equipment to keep in touch with crew members during natural disasters and search-and-rescue missions. Astronomers also use radio waves to communicate with satellites and probes for collecting astronomy data and images of space objects.

This project aims to design an optical communication system as another means of off-grid wireless communication and replace radio in applications where they can fail. Radio waves, depending on the wavelength transmitted, can be negatively affected by space weather through abnormal changes in the ionosphere. Radio equipment can be bulky and/or expensive, especially if operators need to utilize large amounts of power or make line-of-sight communications over long distances. If operators need to transmit large amount of data, radio is not optimal due to its low frequency compared to lasers. An optical transceiver, using a relatively high-power infrared laser and a guidance system, can solve these issues. Coupled with a battery and a computer, it can be an efficient and light setup for transmitting large amounts of data without taking up a large amount of space.

As stated before, FSO communications were already implemented in satellite-based communication systems. Notable examples include NASA's Laser Communications Relay Demonstration (LCRD), the TeraByte InfraRed Delivery (TBIRD) from MIT's Lincoln Laboratory, and the TeraNet from the International Center for Radio Astronomy Research of the University of Western Australia, and the High throughput Optical Network (HydRON) of the European Space Agency.

C. Goals and Structure

This project will start with achieving the translation of digital signals to optical signals by developing a system with pulse-coded modulation and using a laser with a TTL (transistor-transistor-logic) circuit, and maximizing signal reception by constructing an efficient optical system and selecting a photodiode that can receive the wavelength of the laser, which is 980 nm.

After designing the system, we can program a microcontroller and integrate AI/machine-learning capabilities for real-time decoding of optical signals. Signal transmission can be further optimized by simulating the most efficient optical system and searching for different types of lenses and mirrors.

To further develop this system for real-world applications, we can develop this system into an optical transceiver with small form factors and introduce higher-frequency lasers and electro-optical components for larger data transmission.

This paper will be divided into 7 sections: System Overview, Hardware Detail, Software Detail, Demonstration Setup and Procedure, Challenges and Future Work, and Conclusion.

II. SYSTEM OVERVIEW

The digital free-space optical communication system is composed of five primary subsystems: the transmission module, the optical alignment path, the receiving and amplification circuit, the digital decoding and processing unit, and the output display interface. Each subsystem is composed of several interdependent components designed to work in sequence to transmit, detect, decode, and display binary data in real time using a high-power visible laser and a photodiode-based receiver.

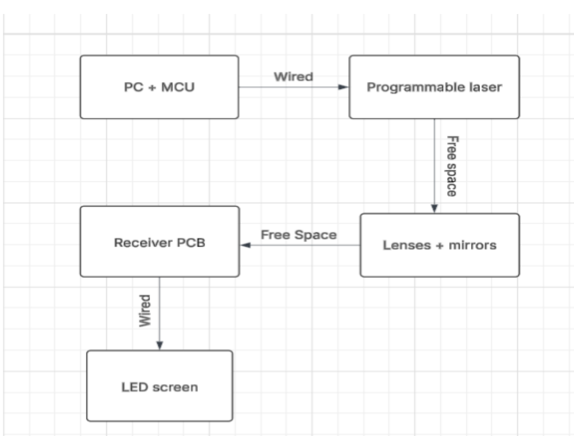

Fig. 1. System Diagram

The transmission module consists of a low power infrared laser mounted to a mechanical holder. The laser is modulated using a microcontroller digital output pin, toggling at a fixed frequency to represent binary data. This modulation simulates an on-off state on the laser to communicate. These states represent logical ‘1’ and ‘0’ through the presence or absence of light. The laser is powered through the same microcontroller that will be connected via USB to the initial computer terminal.

The optical alignment path includes fixed-angle glass lenses and first-surface mirrors, precisely aligned to direct the laser beam across a constrained optical corridor. This setup will minimize beam divergence and ensure that the signal maintains a consistent intensity at the receiving plane. Mechanical 3D-printed holders are used to secure the components in a repeatable and stable configuration.

The receiving circuit begins with a silicon PIN photodiode, which converts optical energy into a small photocurrent. This current is amplified using an OPA381 transimpedance amplifier (TIA), converting it into a measurable voltage. The analog signal is routed to the analog-to-digital converter (ADC) input of the system’s microcontroller for real-time sampling.

The digital processing unit is built around an ATmega328P microcontroller. It samples the analog signal at fixed intervals and uses a threshold-based detection algorithm to reconstruct binary data from the TIA output. Data bits are buffered and grouped into 8-bit segments to reconstruct ASCII characters. The logic includes real-time signal edge detection, bit synchronization, and timeout handling to reduce false positives and improve decoding accuracy.

Finally, the output display interface consists of a 20×4 character I²C Liquid Crystal Display (LCD). After successful decoding, characters are transmitted to the display buffer. The system outputs each received ASCII character to the LCD in a continuous scrolling fashion, with line and character resets implemented to avoid overwriting.

Together, these systems demonstrate an end-to-end physical layer implementation of a digital optical communication link, capable of wirelessly transmitting data across air using visible light.

III. HARDWARE DETAIL -CURTISS

The hardware implementation of the optical communication system integrates discrete analog and digital components into a modular architecture designed for signal integrity, compactness, and low power consumption. This section describes the four major hardware subsystems: the transmitter, optical path, receiver and decoding circuit, and the power system.

A. Transmitter Design

The transmitter consists of a low power infrared laser controlled by a Texas Instruments MSP430G2553 microcontroller. The MSP430 toggles the laser diode on and off to represent binary data using on and off modulation. A digital output pin is configured with precise timing routines to ensure uniform bit intervals, allowing downstream decoding to be synchronized to expected transitions. The microcontroller itself is programmed via a TI LaunchPad development board and operates at 3.3 V logic levels, interfacing cleanly with other system components.

B. Optical Path Integration

To preserve signal fidelity over distance, a precisely aligned optical path is constructed using glass lenses and first-surface mirrors mounted in mechanically rigid 3D-printed frames. The laser is focused using a convex lens to minimize divergence and maximize the intensity of the beam at the receiver. A pair of adjustable mirrors redirect the beam around obstructions and allow for fine-tuned alignment within the testbed. The optical components are mounted with tolerance-controlled holders to reduce misalignment due to vibration or thermal expansion. All mechanical mounts are printed in plastic and designed using CAD tools to ensure modularity and repeatability during assembly.

C. Receiver Circuit

The receiver starts with a silicon PIN photodiode positioned to capture the focused laser beam. This photodiode generates a current proportional to the received optical power, which is converted to a voltage by an OPA381 transimpedance amplifier (TIA). The OPA381 is selected for its high gain bandwidth and low input bias current, essential for accurately resolving low-level photocurrents. The analog signal is sampled by an ATmega328P microcontroller's 10-bit ADC.

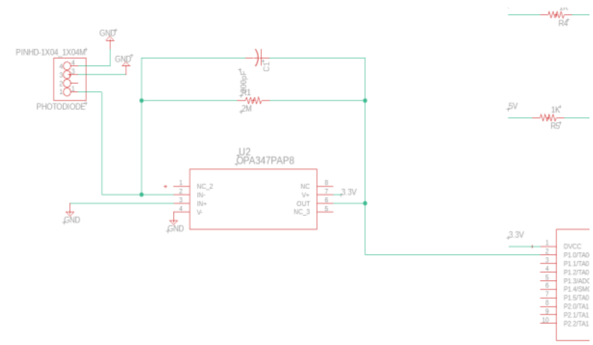

Fig. 2. TIA Schematic

The microcontroller executes a threshold-based sampling algorithm to detect binary transitions and buffer bits into 8-bit groups. These groups are interpreted as ASCII characters, which are then displayed on a 20×4 I²C LCD module. The LCD interface is managed via a lightweight wire library, and scrolling logic is implemented to handle long strings without data overwriting. The microcontroller operates at 5 V, and all analog thresholds are tuned to ensure consistent discrimination between logic '1' and '0' even with noisy signals.

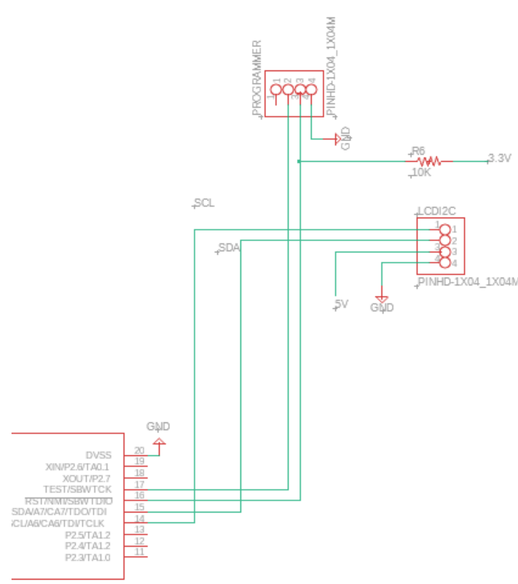

Fig. 3. MCU schematic

D. Power System

The entire system is powered by a 2-cell AA battery holder connected to a pair of boost converters: the TPS613221A and TPS613222A. The TPS613221A boosts the battery voltage to a stable 3.3V rail used for powering the sensitive analog components such as the OPA381. The TPS613222A generates a 5 V rail used by the ATmega328P and the LCD. Both boost converters are selected for their low quiescent current and high efficiency under light-load conditions, extending operational battery life during extended testing. Proper decoupling capacitors are placed close to the regulator outputs to minimize ripple and protect downstream analog and digital systems from supply noise.

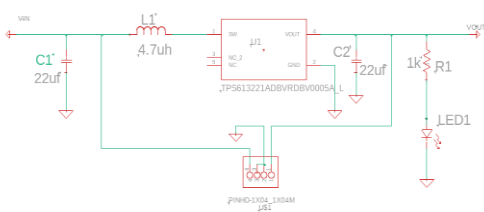

Fig. 4. Regulator Schematic

IV. OPTICAL DESIGN

A. Optical Bench Configuration.

The optical bench is divided into three sections: the laser transmitter, optical guidance system, and the photodiode receiver.

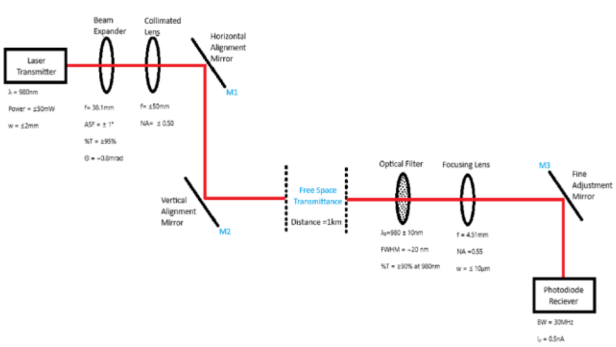

Fig. 5. Optical Diagram

The laser transmitter (top left) consists of a TTL infrared laser connected to a microcontroller that encodes the data into pulses for the laser to transmit. The beam expander and collimation lens enlarge and align the laser beam.

The optical guidance system (two diagonal lines in the middle) uses a set of two mirrors to guide the laser beam to the photodiode receiver across free space.

The photodiode receiver (bottom right) detects the optical signals with a photodiode, which generates photocurrent in response. An optical filter, focusing lens, and fine adjustment mirror filters outside wavelengths and focuses the laser beam tightly into the photodiode. A transimpedance amplifier then converts the photocurrent into an amplified voltage signal that the microcontroller can decode. The decoded signal is then displayed onto an LCD screen.

B. Laser Focusing and Control.

The laser will be expanded with a Galilean beam expander (biconcave + plano-concave), which creates a shorter gap between the lenses, allowing a compact design to be feasible, and no correction lens will be necessary, as this lens configuration will not create a focal point. Maximum signal reception involves slowly adjusting the mirrors and lenses until most of the energy is focused onto the photodiode.

C. Safety Considerations and Physical Alignment Setup

As we are using a Class 3B laser, it can cause eye damage from direct or indirect exposure, so we will encourage ourselves and viewers to wear safety goggles, block reflections, and remove any shiny or flammable materials away from the setup.

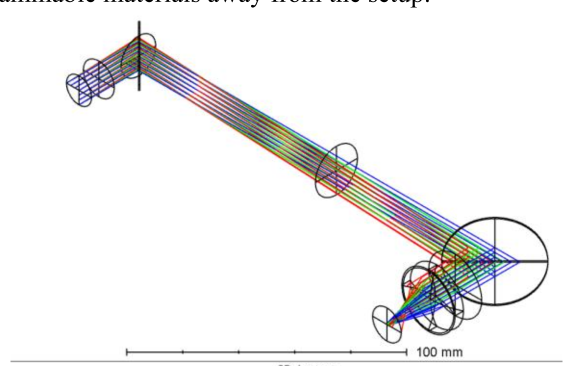

Fig. 6. Zemax Model of Optical Setup

The above Zemax diagram shows approximately the actual physical setup of the communication system. The transmission starts on the top left, where the laser beam is expanded and reflected before travelling across free space. The reception occurs at the bottom right, where the beam gets reflected and then focused into the photodiode.

As the diagram is theoretical, the model will change once we know what the dimensions and types of optical elements we will use.

V. SOFTWARE DETAIL

A. *Flowchart of software logic.*

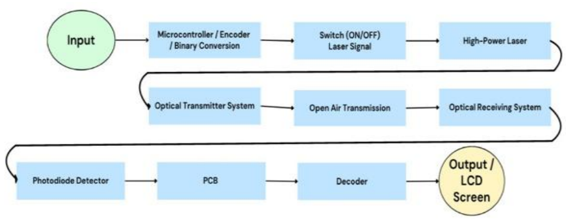

Fig. 7. Software Flowchart

This software design enables wireless data transmission using a high-power laser and optical communication system. Data is input into a microcontroller, encoded into binary, and used to modulate a laser that sends pulses through open air. A photodiode detects the light pulses, which are then converted back into electrical signals, decoded, and displayed on an LCD screen. The system supports high-speed, line-of-sight communication and is ideal for use in environments with limited space, high EMI, or mobility needs. The software manages encoding, synchronization, error handling, and display formatting to ensure reliable real-time operation.

B. *Bit sampling strategy and voltage threshold decoding.*

The system uses a photodiode connected to a transimpedance amplifier (TIA) to convert received optical signals into electrical signals. The output voltage from the TIA is then sampled by the microcontroller's ADC (Analog-to-Digital Converter) to interpret binary data.

The bit sampling strategy is time-based, meaning the microcontroller samples the incoming signal at fixed intervals synchronized with the known bit duration of the transmission. This method relies on precise timing controlled by the microcontroller to ensure accurate bit alignment.

For voltage threshold decoding, a fixed voltage threshold is defined. If the sampled voltage is above the threshold, the system interprets it as a binary '1'; if below, it is interpreted as a binary '0'. This binary stream is then decoded back into characters and displayed on the LCD. This approach ensures clear distinction between light (signal) and no light (no signal), even with minor noise or fluctuations in the photodiode output.

This software strategy enables reliable real-time decoding of optical signals into digital data with minimal error, especially in environments with potential signal distortion or noise

C. *Handling noise, buffering bits, and ASCII reconstruction, etc.*

To handle noise, buffer bits, and reconstruct ASCII characters, the system combines both hardware and software strategies to ensure reliable signal interpretation. On the hardware side, a bandpass optical filter centered at 980 nm is used to block ambient light and isolate the laser's specific wavelength, significantly improving the signal-to-noise ratio. Additionally, the transimpedance amplifier (TIA) is chosen for its low input bias current and high gain bandwidth, which helps minimize electrical noise during the conversion of photocurrent to voltage. In software, a voltage threshold is established so that only voltages above this level are interpreted as binary '1', while those below are treated as binary '0'. This effectively filters out low-level noise. The microcontroller samples the signal at fixed intervals based on a known bit duration, buffering the bits into memory as they are received. Once eight bits are collected, the system reconstructs the corresponding ASCII character using a binary-to-ASCII conversion routine. The character is then sent to the LCD for display. This process of sampling, thresholding, buffering, decoding, and displaying is executed continuously, ensuring real-time and noise-resistant communication over the optical channel.

VI. DEMONSTRATION SETUP AND PROCEDURE

A. Scaled-down Optical Bench Configuration

To evaluate system performance without access to a 1 km test range, a scaled-down optical bench was constructed. This benchtop prototype maintained the proportional geometry and alignment constraints of the full-scale design. Key components included the 980 nm TTL-modulated laser diode, an aspheric collimating lens for beam shaping, dielectric mirrors for directional adjustment, and an FDS100 silicon photodetector as the receiver. Although optimized for visible to near-IR wavelengths (peak responsivity at ~900 nm), the FDS100 remains moderately responsive at 980 nm, albeit with a slightly reduced efficiency of ~0.2 A/W. The rail-mounted platform allowed precision alignment via translation stages and kinematic mirror mounts. Distances between the transmitter and receiver were scaled to account for beam divergence, and optical power levels were adjusted accordingly. This setup enabled laboratory evaluation of the system's transmission stability, signal integrity, and sensitivity to angular misalignment. (see Table VII.1 for angular sensitivity data).

B. Laser Toggling and Bitstream Emission

The system's laser was modulated using a TTL-compatible microcontroller programmed to emit a digital bitstream. Modulation patterns included static binary sequences (e.g., alternating 010101010) and pseudo-random data to test signal decoding. The optical signal, once transmitted across the scaled bench, was captured by the photodetector and converted into a voltage signal by a transimpedance amplifier (TIA). This output was then monitored using an oscilloscope and digital logic analyzer to validate edge detection and pulse clarity. By adjusting the modulation rate and bitstream structure, the team tested receiver response, data fidelity, and the ability to detect digital transitions under varying alignment and power conditions.

The measured values from these tests are shown in Table VI.**1** below. These results highlight how bit error rate (BER) and signal amplitude degrade with increasing bit rate due to photodiode rise/fall limitations and alignment sensitivity.

Table VI.1 - Laser Modulation Test Results

Bit Rate (Hz)	Rx Voltage (Vpp)	BER (Estimate)
1	0.25	~0
10	0.25	~0
50	0.25	~0
100	0.24	~0
500	0.23	$<10^{-5}$
1,000	0.21	$\sim10^{-4}$
2,500	0.18	$\sim10^{-3}$
5,000	0.14	$\sim10^{-2}$

C. Safety Considerations and Physical Alignment

Due to the use of a 980 nm near-infrared (NIR) laser outside the visible spectrum, strict adherence to laser safety protocols was necessary. The optical path was shielded with matte-black barriers to minimize stray reflections. Class 3B laser labels were applied, and IR viewing cards were used during alignment to verify beam position. The alignment itself requires iterative adjustments using micrometer-controlled mounts and visual feedback via a beam target or sensor signal response. During all alignment and operation phases, laser safety goggles rated for 980 nm were worn. The entire bench was operated in a controlled lab environment to eliminate ambient IR interference and ensure safe experimentation.

VII. CHALLENGES AND FUTURE WORK

A. Receiver Sensitivity Limitations and Alignment Difficulties

One of the most significant challenges was the photodetector's limited field of view and angular tolerance. Small misalignments led to drastic reductions in received signal amplitude, and even sub-degree angular deviations caused bitstream corruption or loss. Environmental IR noise, including reflections from lab surfaces and equipment, introduced signal fluctuations and false triggering in the amplifier circuitry. These factors made consistent reception difficult without repeated alignments. The angular response of the FDS100 was characterized in the lab, and results are presented in **Figure VII** below. As shown, even a ±5° angular offset resulted in over 35% signal loss, emphasizing the need for highly accurate beam alignment. A future solution may include auto-alignment feedback systems or beam-tracking mechanisms to dynamically maintain link integrity.

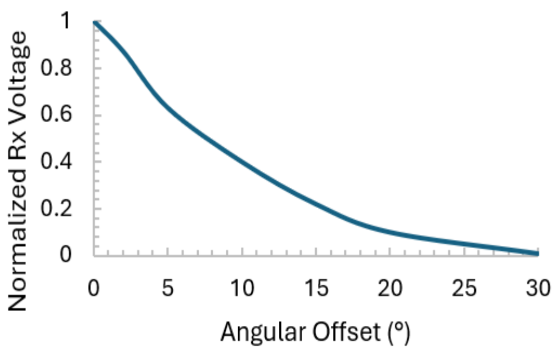

Fig 8. Estimated relationship between Rx Voltage and Angular sensitivity of the FDS100 Photodiode

B. *Ideas for Improving Signal Conditioning and Bit Accuracy*

Current receiver design uses basic threshold-based amplification, which limits performance in high-noise or low-power conditions. To enhance bit detection accuracy, the system could incorporate high-speed comparators with hysteresis, active filtering circuits, and adaptive gain control. A digital phase-locked loop (PLL) or clock-data recovery (CDR) system could be added to synchronize timing and reduce jitter at higher transmission speeds. These improvements would help ensure that pulse edges are accurately captured and reduce bit errors caused by timing misalignment or noise spikes.

C. *Potential Enhancements in Range, Weatherproofing, or Bidirectional Communication*

The current setup focuses on unidirectional mid-range communication. For future applications, increasing range can be achieved by integrating beam expanders to reduce divergence, higher-powered lasers, or optical amplification. To support outdoor or real-world deployment, weatherproof enclosures with hydrophobic optical windows would be essential to protect against fog, rain, and particulate buildup. Further, implementing a dual-channel or wavelength-division multiplexing (WDM) scheme would allow for full-duplex communication. This would enable real-time handshaking, error correction protocols, and interactive control systems suitable for networked FSO links or sensor applications.

VIII. CONCLUSION

A. *Summary of system architecture and demonstration outcome.*

The completed system successfully demonstrated a functional free-space optical communication link using a high-power laser and photodiode receiver. The architecture—centered around a microcontroller, laser diode, optical components, and signal processing circuitry—enabled reliable transmission of binary-coded data over open air. The system effectively converted ASCII characters into binary, modulated the laser to emit corresponding light pulses, and decoded the received signals back into readable text with high accuracy. Key features such as voltage thresholding, bit buffering, and real-time ASCII reconstruction ensured clear and noise-resistant communication. During the final demonstration, the system consistently transmitted and displayed messages like "SOS," validating the hardware and software integration. The project's success highlights the potential of laser-based communication for lightweight, portable, and interference-free data transfer in environments where traditional radio or wired systems may fall short.

A. Reflection on team workflow, problem-solving, and technical learning.

Throughout the development of this project, the team demonstrated strong collaboration, adaptability, and a commitment to continuous technical growth. Each member contributed their expertise in areas such as optical alignment, embedded systems, PCB design, and software development, allowing the group to work efficiently and solve problems as they arose. One major challenge was achieving accurate signal detection from the photodiode due to noise and amplification inconsistencies. This was addressed through careful tuning of the transimpedance amplifier and refining the voltage threshold decoding in software. The team also leveraged the MSP430 microcontroller's features for real-time processing and LCD output, gaining valuable experience with Code Composer Studio, embedded C programming, and bit-level data handling. Through hands-on testing, iterative debugging, and shared learning, the team not only delivered a functional optical communication system but also strengthened their skills in system integration, hardware-software co-design, and collaborative engineering.

The Engineers

Alexander Simmons is 25 years old-graduating Photonics Engineering student. He plans to pursue a hands-on role with contractors like L3Harris or Leonardo DRS, or at Eglin AFB, to gain experience in electro-optical systems and fiber optics after graduation.

Curtiss Kane is 23 years-old graduating Electrical Engineering student. He plans on using applications of Electrical Engineering in the field of Non-destructive Engineering.

Ivan Huang is a 22-year-old graduating Photonics Engineering student. He plans to enter the renewable energy or telecommunications industry after graduation.

Monica Castro-Suarez is a 26-year-old graduating Computer Engineering student. Her career goals include furthering her knowledge in network engineering. She aims to work at top tech companies like Cisco, Google, or Apple, or contribute to innovative projects in themed entertainment at Universal Creative or Disney Imagineering.

IX. REFERENCES

1) Schauer, K. "Exploring Together, NASA and Industry Embrace Laser Communications". NASA, 2021. https://www.nasa.gov/technology/exploring-together-nasa-and-industry-embrace-laser-communications/
2) Tantillo, A. "Communications system achieves fastest laser link from space yet". MIT Lincoln Laboratory, 2022. https://news.mit.edu/2022/communications-system-achieves-fastest-laser-link-space-yet-1130
3) Boyd, J. "Terabit-Scale Tech Tests Satellite-to-Earth Laser Link > Network of ground stations insures against cloudy skies". IEEE Spectrum, 2024. "https://spectrum.ieee.org/laser-satellite-communication
4) ESA. "HydRON: Satellites using lasers for faster data sharing". 2024. https://www.esa.int/Applications/Connectivity_and_Secure_Communications/HydRON_Satellites_using_lasers_for_faster_data_sharing
5) Newport Corporation. "How to Build a Beam Expander". https://www.newport.com/n/how-to-build-a-beam-expander
6) *"Based on Hamamatsu's spectral response curve for silicon photodiodes, the FDS100 exhibits approximately 0.18–0.22 A/W responsivity at 980 nm."* *— Ref: FDS100 Datasheet, Hamamatsu*