LOCC: Enabling the Characterization of On-Orbit, Minimally Shielded LEDs

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ABSTRACT

Over the past decade, trends have shown a substantial growth of interest for small satellite solutions, ranging from earth-orbit imaging to cheap global communication networks. Along with space-based applications, several research missions are focused on testing novel sensors and materials, group III-V nitride semiconductors being among them. Small satellite missions provide a unique opportunity to gain an understanding of the reliability and operational characteristics of these materials when exposed to the harsh environment of space. Such insight will lead to unique space applications of these materials in larger missions. While the nature of electronic and optoelectronic devices involving III-V materials under the bombardment of ionizing radiation has been reported, these findings have mostly been established via controlled tests in terrestrial laboratories.

In this work, a Low-powered Optoelectronic Characterizer for CubeSat (LOCC) has been developed to perform in-situ current-voltage measurements of III-V nitride based optoelectronic devices on-orbit. Lastly, it is important to note the use of III-V nitride materials in this experiment. Custom InGaN LEDs have been fabricated with a center emission wavelength of 465 nm The LOCC system includes a spectral confirmation module that is used for luminescence characterization of the devices. While most current-voltage measurement instruments are made for laboratory benches and consume higher amounts of power, this system is designed using low-power integrated circuits that are capable of supplying the necessary current while maintaining low-power operation. The system must also operate within the data transfer and storage limitations of the CubeSat platform. LOCC is designed to transmit the experimental results to the satellite's controlling computer via an I2C bus. The characteristics of low-power consumption and small information storage requirements make LOCC an excellent match for this science mission.

This paper details the design and control of the LOCC system. The design includes block diagrams, PCB layout, interfacing, and control. Additionally, the resulting current-voltage measurements, required wattage, and required data storage will be presented to illustrate functionality. This instrumentation will enable the study of III-V nitride based optoelectronic devices in space, as well as parallel advancements of electronics and optical sensors that can be used for short-distance range finding and shape rendering systems for satellite servicing missions.

INTRODUCTION

In recent years the White House has promoted the 'maker initiative' to help bolster the creation of new and innovative technologies throughout the United States. Supporting this, NASA will work towards assisting all 50 states in launching small satellites over the next few years. Recently, NASA selected a multidisciplinary group from West Virginia to develop and launch the state's first Cubesat. In this effort, West Virginia University is joining with NASA IV&V Independent Test Capability (ITC) team to launch a 3U sized Cubesat titled Simulation-to-Flight (STF-1). The STF-1 mission is scheduled to be launched June 2017 on board the Educational Launch of NanoSatallites (ELaNa) XIX from Rocket Labs, USA. This launch and mission provide the students of WVU and team members of NASA IV&V an unprecedented opportunity for the advancement of technologies and understanding, helping pave way for the growth of the CubeSat initiative.

The primary objective of the STF-1 mission is the validation of test platforms for transitioning technologies in the development phase to flight-ready components [1]. The secondary objectives include experiments from three different WVU departments: the Department of Physics in the Eberly College of Arts and Sciences, and the Mechanical and Aerospace Engineering Department and the Lane Department of Computer Science and Electrical Engineering in the Statler College of Engineering and Mineral Resources. These experiments involve the testing of a MEMS IMU Swarm prototype, GNSS Receiver and Precise Orbit Determination, Magnetosphere-Ionosphere Coupling and Space Weather, and the characterization of III-V

Nitride-based LEDs. These objectives make way for advancement of technology for space exploration.

The harsh environment of space requires silicon-based electronics, including Light Emitting Diodes (LEDs), Laser Diodes (LDs), Photodetectors (PDs), Photovoltaics (PVs), and field effect transistors (FETs), to be shielded or otherwise protected from potentially high levels of radiation and large temperature swings. This shielding increases the overall weight of any launch vehicle, leading into an overall reduction in payload capacity. There is a lack of equipment and methods to study the effects of space on these types of devices, [2]. III-V Nitride-based LEDs and other electronic components possess a natural hardness against ionizing radiation and high-temperatures [3], making ideal replacements for silicon electronics in space applications. However, as with silicon electronics it is difficult to test this hardness in terrestrial experiments. A CubeSat mission provides an ideal platform for measuring LED and photodetectors responsivity, I-V characteristics, junction temperature, and electroluminescence in the space environment. A low-powered optoelectronic characterizer for CubeSat (LOCC) has been developed to meet these demands.

LOCC is a low-power, CubeSat specific instrumentation module that utilizes a combination of discrete components to measure the I-V characteristics and partial electroluminescence of chip carrier packaged InGaN-based LEDs. The results from on-orbit I-V and electroluminescence measurements are stored locally, using kilobit-sized data packets for each LED or PD sensors. With small data size and low-power operation, LOCC enables the study of the effects of space on optoelectronic devices. The design, development, and results of the LOCC platform are detailed further in this paper.

III-V Nitride-Based LEDs

The LEDs used in the LOCC module are fabricated in the WVU Shared Cleanroom Facility, using an architecture developed in previous and ongoing solid-state lighting research efforts [4], [5] ,[6]. Fabrication of these LEDs follows common semiconductor processing approaches, including nitrogen assisted annealing, photolithography, wet and dry etching, and metal deposition. The metal contacts were formed with alternating layers of titanium, aluminum, and gold. Figure 1 illustrates an optimized LED structure.

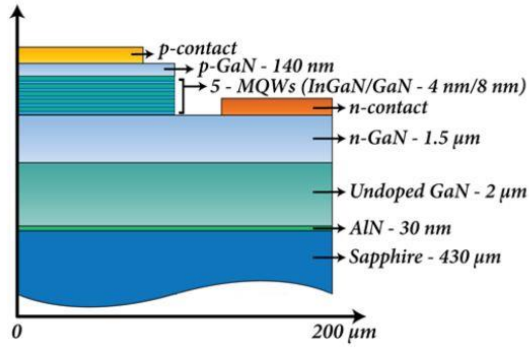

Figure 1. Optimized LED structure

Experimental Overview

When testing the LEDs and their respective photodiodes sensors while in space, it is important to establish a control group of devices in order to accurately interpret the results of the experiments. A layer of transparent conformal coating will be added to the boards comprising LOCC system. This conformal coating will give us the necessary shielding to minimize the potential for damage to the control devices. Three pairs of LED/PDs will be used, as seen in Figure 2. As shown on the left of Figure 2, Set A will consist of both LEDs and PDs being coated. The middle Set B array will consist of coated PDs and uncoated LEDs. For Set C on the right, both LED and PD devices will remain uncoated. A comparison of the uncoated and coated devices will allow for the effects of the space environment on the unprotected InGaN LED devices to be monitored via device characterization methods, which will be described in the following sections.

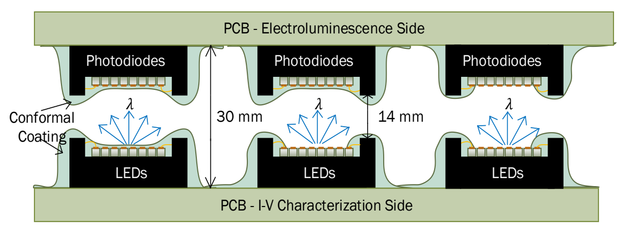

Figure 2. (Left) Set A, Both LED and PD array conformally coated. (Middle) Set B, Only PD coated. (Right) Set C, No device coatings.

Device Characterization

A major goal of the LOCC module in this CubeSat mission is to gain an understanding of the LEDs active region and its relation to temperature. Two methods of determining junction temperature will be applied. It has been shown that junction temperature is related to the resistance and forward voltage of an LED [7], [8]. Utilizing the electrical measurements of current versus voltage, the junction temperature swing under conditions of both atmospheric temperature and the effect of ionizing radiation can be examined. Figure 3 shows a sample current-voltage relationship of the in-house fabricated LEDs.

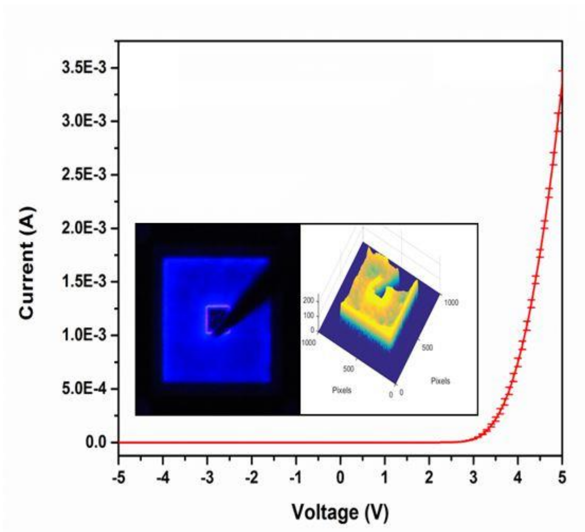

Figure 3. Current-voltage relation of in-house fabricated LEDs

Electroluminescence measurements will be performed in parallel with LED electrical measurements. Here, junction temperature can be estimated as a shift in peak wavelength [9], [10]. A sample spectral emission plot from the in-house fabricated LEDs is shown in Figure 4. These techniques for characterizing LEDs allow for a unique look at the operation of optoelectronic devices and their efficiencies while on-orbit. Additionally, these characterization methods allow for comparison and confirmation of the experimental results.

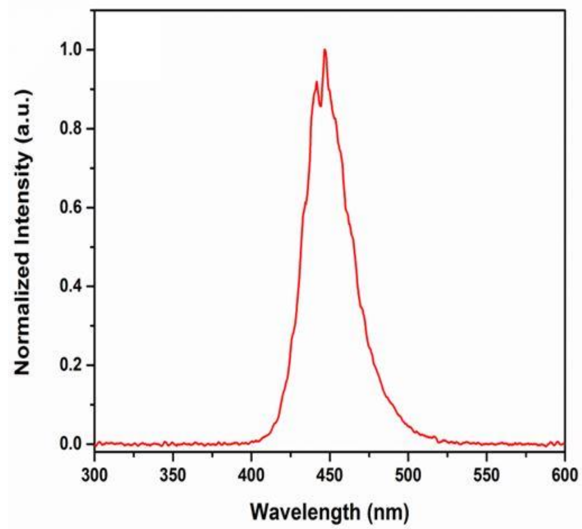

Figure 4. I-V and Spectrum Characteristics of in-house fabricated LEDs

For the application of spectral measurements, and to aid in the observation of peak wavelength shift, reliable photodiodes are required. This component of the LOCC system will use commercially available visible-spectrum Si-PIN photodiodes that have been shielded to prevent corruption of the LEDs characterization experiments. Multichannel sensors have been selected due to their flexibility and ease of adaptation based on experimental demands. [11].

HARDWARE DESIGN

The design and layout of the LOCC module are based on the size constraints of the PC104 specification and power and data limitations of the CubeSat platform. Figure 7 illustrates a how the LED component and photodiode component boards of the LOCC module will fit together. Figure 5 shows the system overview.

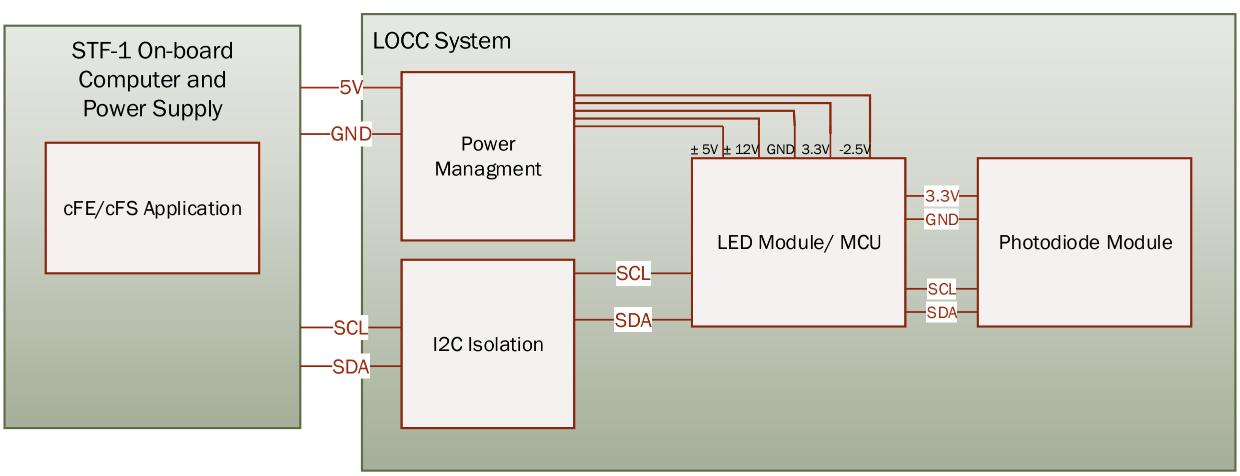

Figure 5. Block diagram describing LOCC system and governing module

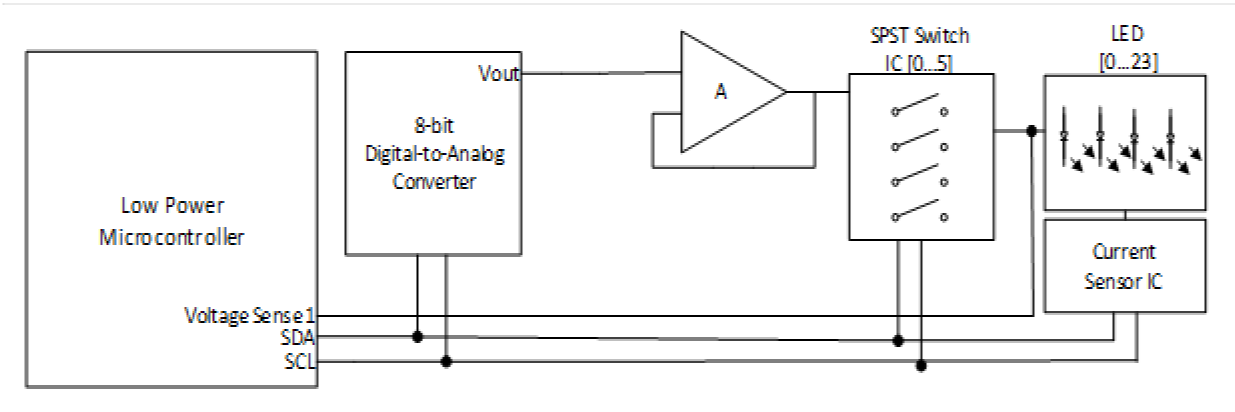

Figure 6. Block Diagram of LED characterization module

The design of the LOCC module allows for future designs to scale power and available space based on the number of electronic devices and size of small satellites. A stacked configuration is utilized in order to spatially align the LEDs and commercial photodiodes. Both PCBs are governed by four major hardware modules that include: power management, communication isolation, LED I-V characterizer and microcontroller, and the electroluminescence characterization unit. These components will be described in the following sections, followed by a brief overview of the software and firmware that marries the components of the LOCC system with the computer of STF-1. Lastly, the PCB layout is provided. This will serve to describe board layers, split planes, traces, and component placements.

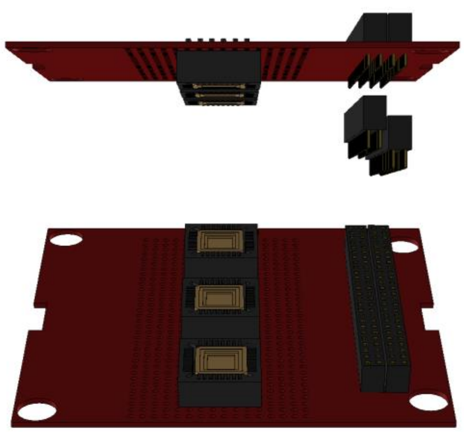

Figure 7. (Top) Mock photodiode module, (Bottom) mock LED module LOCC system stack

LED characterization module

Figure 6 provides a block diagram of the LED characterization module. A low-power Arduino microcontroller to control the LOCC experiments, which allows for programmable configuration of LED switching, voltage ramping, voltage sensing, and data management. The embedded microcontroller and the main onboard computer of the CubeSat communicate directly to control the timing of experiments and transmission of collected data. To achieve the required 0V to 5V voltage ramp, an 8-bit digital-to-analog (DAC) IC is utilized. To provide the LEDs with sufficient current a high-current-output operational amplifier is used. This allows the LEDs to be ramped from 0V to 5V, as well as source enough current to avoid voltage capping. It should be noted that, for ensuring proper output, the op-amp is configured with 12V supply voltage. The LED characterization module includes redundant components so the characterization experiments can be performed on multiple LEDs over the course of the mission. This redundancy will also mitigate the loss of LEDs due to damage or other malfunction by allowing for spare LEDs to be activated at later times. For the operation of ramping, multiple LEDs six single-throw, single-pole (SPST) switching ICs with high current throughput and low resistance are used for device selection, assuring that only one LED is activated at a time. It is crucial when selecting SPST switches for LEDs as a small on resistance is needed along with the ability to allow for voltage swings. Here, the switches also operate on 12V input voltage to allow the LED driver voltage to ramp from 0V to 5V. The selection of LEDs is accomplished simply by using the inter-integrated circuit (I2C) enabled addressing that is built into the devices. Most components onboard the LOCC system utilize the microcontroller's ability to assign data and clock lines to select pins. This allows for a separation of internal I2C device communication and onboard computer I2C communications. To achieve this, LOCC uses software rather than hardware to achieve its communication with PCB components.

This is commonly known as 'bit banging,' and provides clean signals and enables interrupts to be received at any time from the main computer. For the last portion of this module, the current passing through the LED devices needs to be monitored and recorded using a current sensor. The current sensor is configured with a shunt resistor and the device measures this voltage change to determine how much current is flowing through the device. Using the built-in analog-to-digital converter (ADC) and I2C interfacing, a mA-accurate current reading can be attained and sent back to the microcontroller.

Electroluminescence characterization module

A similar approach and setup to that of the LED characterization module is used for electroluminescence measurements. This allows for the photodiode sensor to be activated and measured with the proper biasing voltage as recommended by the manufacturer, making it possible to view any wavelength shifts that may occur from the selected LED. It is necessary to calibrate color measurement for this application to ensure for measurements that fall into color space. The calibration function includes converting the measured values from the analog-to-digital converter into color space. It also includes a compensation for PD tolerances. Lastly, the accuracy of the calibrated sensor is sensitive the environment and must be corrected as things like temperature can affect the system's components. The desired LED can then be selected and turned on via the LED characterization module's digital-to-analog converter and held at a constant voltage. Once these steps have been achieved, the current can then be recorded and sent back to the MCU. Currents passing through photodiodes can range anywhere from picoamps to microamps, depending on structure and application. For measuring these values, an analog-to-digital converter equipped with I2C control is used. This devices allows for a high sensitivity for small current measurements, and is resistant to temperature drifts. This component configuration allows for high sensitivity and accuracy of photodiode current measurements, which, in turn, provides the needed experimental stability to obtain consistent, reliable results. Figure 8 shows the block diagram of the photodiode component module.

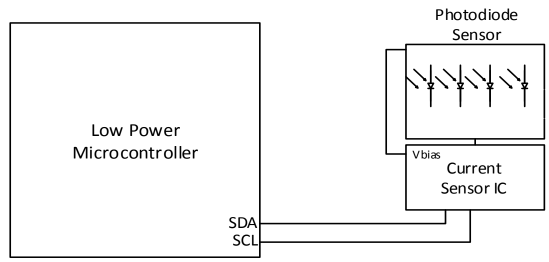

Figure 8: Block diagram of electroluminescence characterizer module

Due to the science goals of the mission and the sensitivity of these current measurements, this component of the LOCC system must be the most stable. Temperatures and radiation can have detrimental effects on the Si-based solid-state electronics, and will easily corrupt any results that may be obtained. To mitigate these issues proper heat sinking and radiation shielding (in the form of conformal coating) of the various Si-based components must be taken into account (as mentioned earlier)

Power management module

Proper power management is fundamental to the operation of the LOCC system and its characterization experiments. This module is in place to create the necessary supply voltage needed to run each component. Because power buses are susceptible to uncertainties from the supply or other experiments, it is necessary to provide electrical isolation and over drawing current protection. In addition to providing the necessary power, the DC-DC converters electrically isolate and provide short circuit protection for LOCC from the CubeSat's power bus. Following the necessity of protection, the DC-DC converters supply the rest of the LOCC system with isolated ground, 5V, and 12V for the PCB power planes. The 12V supply is specifically used to maximize proper voltage swings for the electrical characterization of LEDs. This ensures the system's ability to ramp voltages between 0 and 5V. The 5V supply is used to power the majority of components of the system, helping maintain a low power demand. To provide for lower voltages and offsets, two additional components are included in the design. A supply for 3.3V is also included to power the required ICs needed for spectral measurements. This uses an additional DC-DC converter.

The calculated power requirements of the LOCC system are shown in Table 1. The power budget includes all components on both the LED portion and the photodiode portion.

Table 1: Power budget for LOCC system

Power Budget	
Total (TYP) (W)	.437
Total (MAX) (W)	.618

I2C Interfacing module and data

The onboard computer for STF-1 communicates with the LOCC-specific system components via I2C communication protocol. The LOCC system utilizes I2C to communicate between its components and the microcontroller unit. The microcontroller then communicates with the master computer of the CubeSat. For this, an I2C interface has been implemented onboard the LOCC system to meet STF-1's communication requirements.

Like the power bus, the communication bus is also susceptible to faults and uncertainties. The I2C interfacing module provides protection for the LOCC's communication to and from the rest of the PCB. The interfacing also ensures against pulling the communication bus voltage down through the use of optical isolation. This decoupling device is a monolithic form, multi-channel, and bi-directional optocoupler. The device allows for multiple configurations, and for this arrangement is set for three channels, bi-directional operation. Also included in the communication interfacing is a bi-directional bus buffer for ensuring data and clock signal integrity while data and other signals pass between the main computer and LOCC. The bus buffer is also useful in reducing bus capacitance, reducing the total loading on the communications bus. Lastly, this module includes a single buffer/driver with open-drain output. This device also helps ensure signal integrity by design for high drive for wired-OR/AND functions.

The LOCC system uses a combination of standard Arduino software libraries, open source libraries, modified libraries, and custom libraries developed specifically for certain components. Because the ability to interrupt the device at any time is required, the I2C processing is split between the hardware signals coming from the main computer that include serial data and serial clock lines and a software controlled I2C function known as bit banging. This allows for seamless communication between the MCU and components without interference from the onboard computer and vice versa.

Table 2: Pre-allocated parameters for LOCC

Variable	Size (Bytes)	Description
Counter: Current LED	1	A counter showing the current LED being used in the experiment
Voltage Resolution	1	The number of data points gathered for each LED
LED Select	3	Used to choose individual LEDs
LED Status	3	A set of flag bits representing the working status of LEDs
Experiment Frequency	1	Used to determine how often experiments will be run over the course of a week

Data will initially be stored on the LOCC on-board EEPROM, with a capacity of 4096 bytes. A set of memory addresses in the EEPROM will be pre-allocated for storing parameters and program states. These 9 bytes of memory are defined in Table 2. With these 9 bytes of information in use, the other 4087 bytes of EEPROM are available for experiment data storage, specifically, recorded values of LED and photodiode sensor voltage and current. Data packets sent from the LOCC system, will contain complete data from 1-to-many LEDs and photodiodes. The number of LEDs/PDs in the data packet and the size of the packet will depend on the voltage resolution of the DAC and ADC. The data, timing, and experiment frequency are listed below. For the electrical characterization of LEDs experiment, the data structure for an individual LED will be as listed in Table 3.

Table 3. Electrical characterization data structure

Parameter	Size (Bytes)
LED ID	1
Time Stamp	2
Temperature	2
Measured Voltage	2N, where N is the voltage resolution parameter
Measured Current	2N, where N is the voltage resolution parameter

For electroluminescence characterization, the data structure for an individual photodiode is shown in Table 4.

Table 4. Electroluminescence characterization data structure

Parameter	Size (Bytes)
Sensor ID	1
Time Stamp	2
Lux	1

Measured Voltage	2N, where N is the voltage resolution parameter
Measured Current	2N, where N is the voltage resolution parameter

Note that a different parameter, Lux, is included in the EL spectrum characterization. This value is to signify if the LED has actually turned on. With an adjustable voltage resolution LOCC is able to manipulate the amount of data that will come from the experiments. This will allow for a wide range of storage usage. The resulting data outputs as a result of changing the voltage resolution can be seen in Tables 5 and 6. The number of packets to be transferred is also represented here. To also give perspective of storage need, the data need for all 24 LED/PDs is also listed.

Table 5: Data budget for single LED/PD

	Minimum	Maximum
Data (B)	34	1026
# of Packets	1	1

Table 6: Data budget for all 24 LED/PDs

	Minimum	Maximum
Data (B)	888	24696
# of Packets	1	7

To describe the operation of LOCC, the system begins its routine when power is first established by the main on-board computer. Here the firmware looks to establish connection with the master software. Once the connection is established, LOCC will wait for input commands from the cFE application on which experiment to run, setting of new variables such as voltage resolution, setting the desired LEDs for the experiment, or the retrieval of data. Following this, the selected experiment will be executed. The experiment will run through its process and check to see if data is ready to be sent. If data is ready, LOCC will first tell the parent application how much data is to be sent. Upon acknowledgment, the information can be sent to the application for storage and then transmission to the ground station. Lastly, once the experiment has completed an LED or photodiode measurement, the firmware will check to make sure all information has been sent, and whether or not the next LED will be evaluated. If there are no additional LED/PDs to examine, LOCC will send a shutdown confirmation, and the main on-board computer will switch off the 5V power supply, completing the operation. LOCC has been uniquely designed to operate independently based on command codes sent the module. The user does not need to be concerned with time consuming setups, pin assignment, or communication protocols, allowing for a simple to use device in the lab, office, classroom, or CubeSat.

The I-V graphs displayed in Figure 9 illustrate various ramped voltages and the differences with adjusted voltage sample depths from the DAC. These characterizations were performed on commercially available LEDs to test operations of the LOCC system.

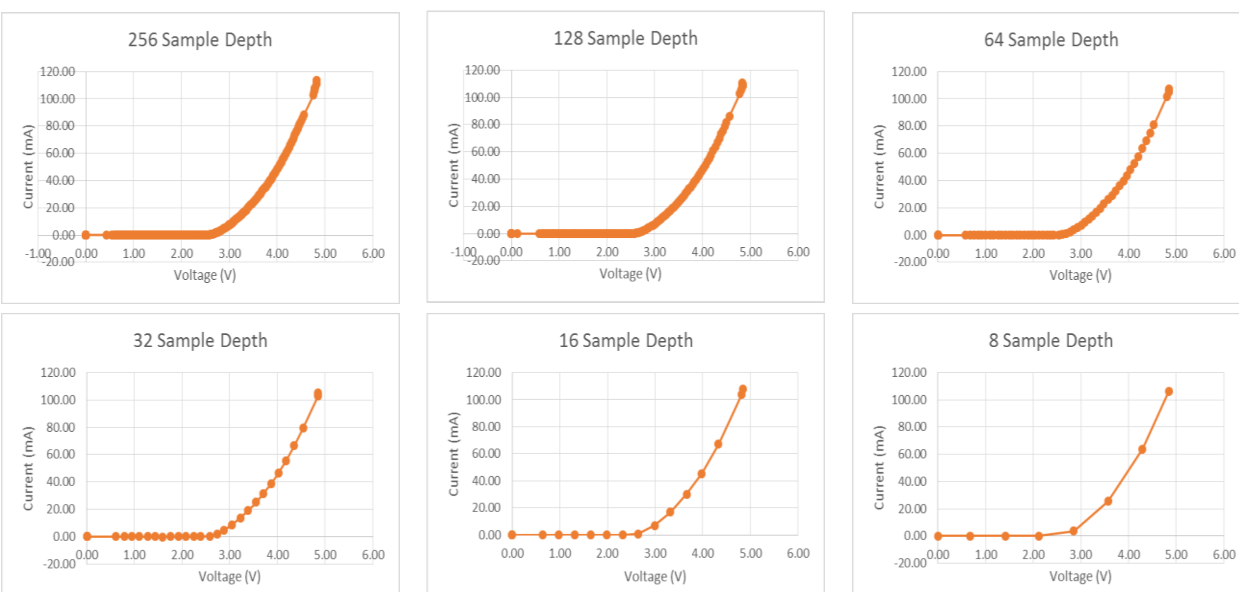

Figure 9. I-V characteristics produced from LOCC prototype

PCB LAYOUT

For the next stage of development all the through-hole components, surface mounted technologies (SMT), and copper traces must be planned out to ensure proper communication as well as adhering to available PCB real estate. Starting at the center plane of the board layers and working outwards, the design is a 4-layer board that utilizes split ground and power planes to provide ease of access for all components and through holes. To enable electrical isolation, the planes have been grouped into the CubeSat system bus power and ground planes and the isolated 5V, 12V, and 0V planes. To make the most efficient use of the limited space, most of the components have been placed on the opposite sides of either the photodiodes or the LEDs. This design allows for multiple modes of powering the system. First, the device is designed using a USB 2.0 specified connection. This connection can power the whole board for the characterization process. Its power input connects directly to the system bus power plane where the DC-DC converters handle the rest of the power distribution. The USB connection is then connected to a USB controller IC. For stability, the USB controller is connected with a piezoelectric crystal that ensures proper data and clock delivery. The USB controller allows a direct interface with the microcontroller unit and an ease use for programming and desktop applications. A second method for device power and communication comes from the stack header pins. These connect the LOCC system in parallel with all the other experiments. A 5V bus supplies up to a maximum of 4.5A. The I2C communication also comes from these pins, bypassing the USB controller and connecting directly to the MCU. The 5V supply from the CubeSat power supply undergoes the same DC-DC conversion as the power from the USB. Following the placement of components, a solid ground pour is used on both the top and bottom sides and tied to their respective system bus grounds and isolated ground. This ground pour provides advantages such as reducing PCB warping, heat sinking, and noise reduction. To accompany these ground pours, via stitching is applied over the entire board to help create a vertically strong connection through the board. It should also be noted that a grounded via fence also wraps around the parameter of the board to help reduce electromagnetic noise. Figures 10 and 11 display the 3-D rendered LOCC system I-V characterizer side from both the top and bottom sides.

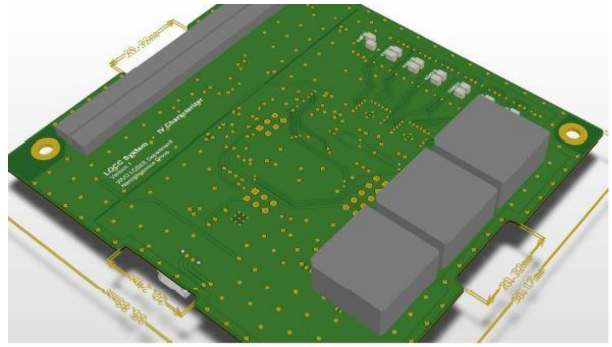

Figure 10. Top side of LOCC system

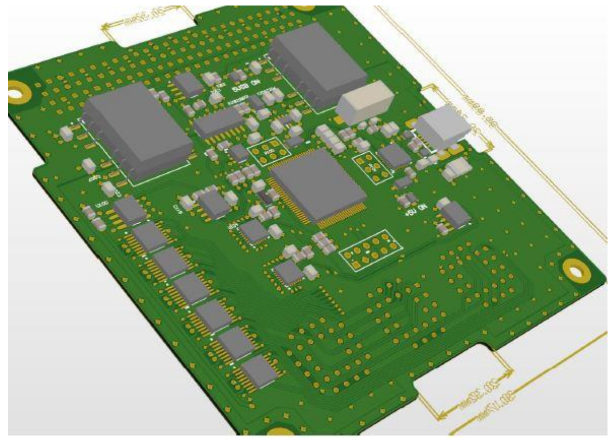

Figure 11. Bottom Side of LOCC I-V Characterizer

SUMMARY

In summary, the development, design, and operation of a low-powered optoelectronic characterizer has been presented. Details regarding communication protocol, power management, electrical characterization, and electroluminescent characterization have been illustrated and mapped together. Currently, LOCC is in the prototyping stage with component procurement, new LEDs, I-V characterizer PCB fabrication, and the EL characterizer board design in line for the coming months.

For the exploration of space, novel electronic devices that are designed to function with a minimal amount of shielding and temperature swing mitigation must be able to withstand the extremes of the native space environment. This CubeSat mission aims to show that III-V nitride-based semiconductor electronics possess both radiation hardness and temperature stability, information that will be determined by measuring the functionality of such devices on-orbit using the LOCC module. This design holds the potential to be a useful tool for advancing our understanding of semiconductor devices and the lifetime and integrity of space-based electronics.

ACKNOWLEDGEMENTS

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