High Frequency InGaN/GaN Micro LEDs for Optical Interconnect Applications

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Abstract

With the increasing relevance of AI models, the demand for specialized high speed computation has grown. To handle the higher processing rates of modern AI hardware, all stages of the pipeline need to follow pace. One major bottleneck in current systems is getting data from the memory to the processor. Optical interconnects are an alternative to the current electrical interconnect, and they have the potential to significantly increase the bandwidth of data transfers, while also reducing power and interference. This project will explore the design methods and tradeoffs when increasing the frequency bandwidth of micro LEDs used in generating the data signals. Specifically it will go over the design choices affecting the rise and fall times of modulating micro LEDs. The results of this research project will provide a better understanding on the benefits of optical interconnects and how it can advance computational speeds. The project's outcome is important in reducing data transmission delays and inefficiencies in high speed processors to ultimately save more power.

Introduction and Motivation

Computing started becoming popular in the mid-20th century with the first digital computers being used in World War II for code-breaking and trajectory calculations. As the technology developed and computers started becoming available to the general population, so did the demand for performance. Since the 1990s and the beginnings of the internet, computing has grown rapidly into an indispensable part of our lives. With the increasing demand for computers, the need for faster and more efficient performance also grew. Transistors were able to scale down and continually increase their speed and power, while reducing area. Unfortunately memory systems in modern processors have fallen behind the improvements seen in processing power [7]. This issue, sometimes called the "Memory Wall", is a major bottleneck in processors that causes inefficiencies in the execution pipeline. The relatively long wait times for memory accesses causes many slow-downs where other instructions could be executed. This reduces the overall efficiency of the processor and leads to more static leakage power. The increasing gap between processing power and memory speeds is shown in Figure 1 below.

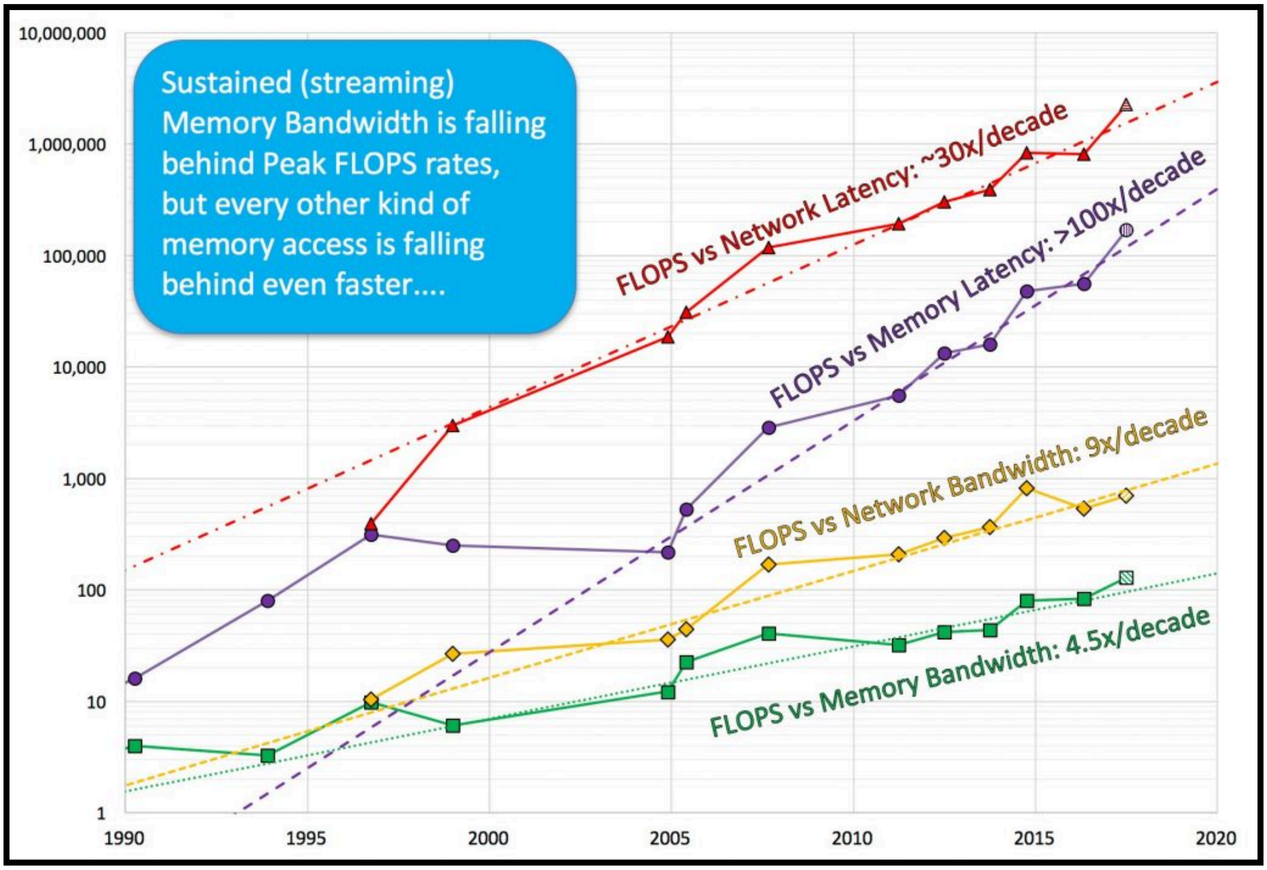

Figure 1: Floating point operation speeds relative to data transfer speeds over time [8]

In nearly all modern processors the standard form of interconnects are electrically based. Currently electrical interconnects dominate due to their compatibility in the manufacturing processes and simplicity. Some drawbacks that electrical interconnects have compared to optical are: lower bandwidths, electromagnetic interference sensitivity, and signal loss over longer distances. As the need for smaller, faster, and more efficient computation arises, optical interconnects offer a solution for faster data transfer speeds, reduced interference, and reduced power usage [4].

With the trend of computers and AI systems being integrated into daily life, the energy costs are ever increasing. Some estimates show ~1000 Terawatt-Hours being used in data centers by 2026 [5]. AI models in particular take thousands of Megawatt-Hours to train, and even more energy each time an interaction occurs [6]. With all these sources of computation requiring power, it is crucial to develop methods to reduce the power of data transfers.

Technical Background

Light-Emitting Diode

An LED is a p-n junction made of semiconductor materials that can emit light through the process of electroluminescence. When voltage is applied between the p and n doped regions, electrons and holes are injected into the junction. These electrons and holes will then recombine and release photons of equivalent energy to the bandgap. A heterojunction can be formed with the addition of one or more quantum wells shown in the figure below. These quantum wells improve the efficiency of the LED and allow for precise control over emission wavelength.

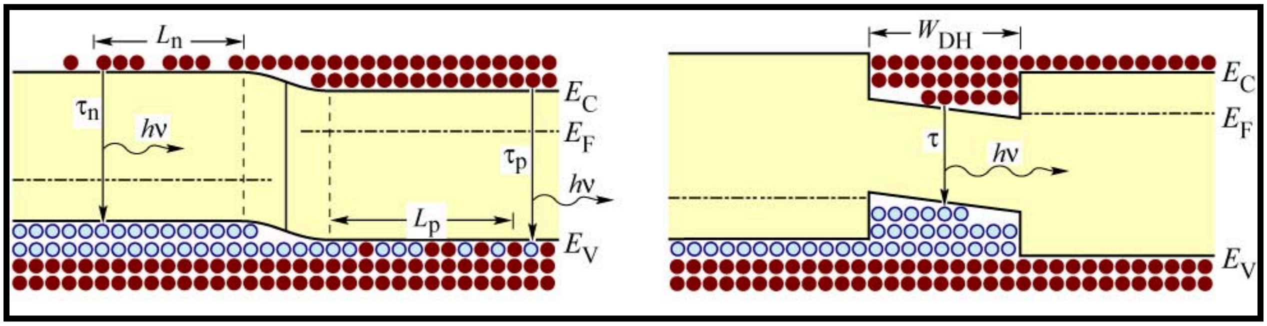

Figure 2: Homojunction (left) LED and Heterojunction LED (right) under forward bias [1]

Wavelength-Division Multiplexing

One common technique of optically transmitting data is wavelength-division multiplexing. This involves sending optical data in the form of pulses, similar to a single bit wire in an electrical interconnect, but instead overlaying multiple different light signals in a single interconnect (Fig 3). Due to the properties of light, these overlapped signals will not interfere which allows for multiplied data transmission density. Furthermore, WDM enables the ability to bidirectionally transmit data over a single optical interconnect channel.

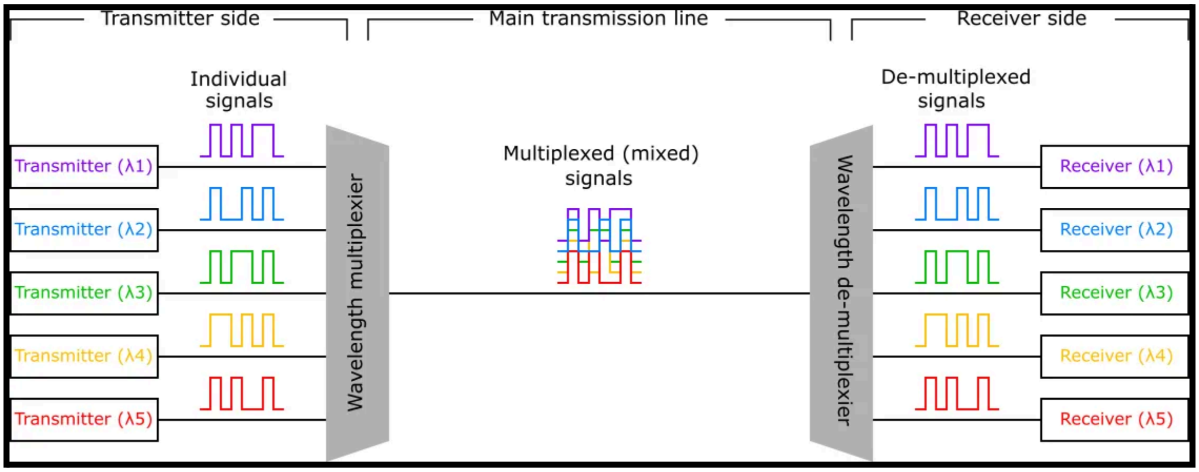

Figure 3: Diagram of WDM operation [2]

Vegard's Law

This project will only be focusing on blue InGaN/GaN based micro LEDs. In order to achieve a blue wavelength of around 500 nm, we need a bandgap of around 2.5 eVs. In its most basic form Vegard's law is a linear interpolation of the two binary compounds' band gaps as a function of composition percentage.

$$E_{g,\,InGaN} = xE_{g,\,GaN} + (1 - x)E_{g,\,InN} \quad (1)$$

In the case of InGaN though, the bowing constant must be taken into account to accurately determine composition. The bowing constant introduces a quadratic change to Vegard's law as shown in equation 2 and figure 4.

$$E_{g,\,InGaN} = xE_{g,\,GaN} + (1 - x)E_{g,\,InN} - \beta x(1 - x) \quad (2)$$

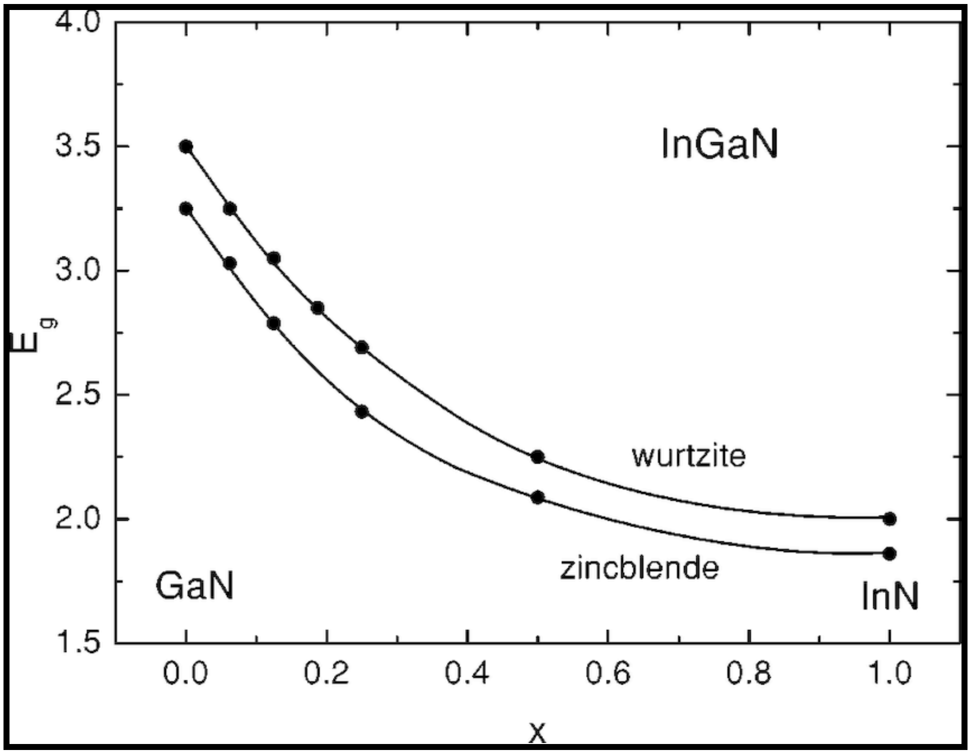

Figure 4: Vegard's Law for InGaN bandgap [9]

Applying Vegard's law with the bowing parameter to an InGaN compound to achieve a bandgap of 2.5 eVs yields a target composition of around 0.2 GaN.

Simulation Design, Results, and Discussion

The simulations of the micro LEDs used in this project were done using Advanced Physical Models of Semiconductor Device (APSYS) in Crosslight software. The structure of the LED, shown in figure 5 below, is a p-n junction of doped GaN with one or more InGaN/GaN quantum wells sandwiched in between. The n-doping of the bottom layer is . The p-doping of the top layer is , and the p-doping of the layer below that is . There are contacts on the first quarter length and last quarter length of the LED.

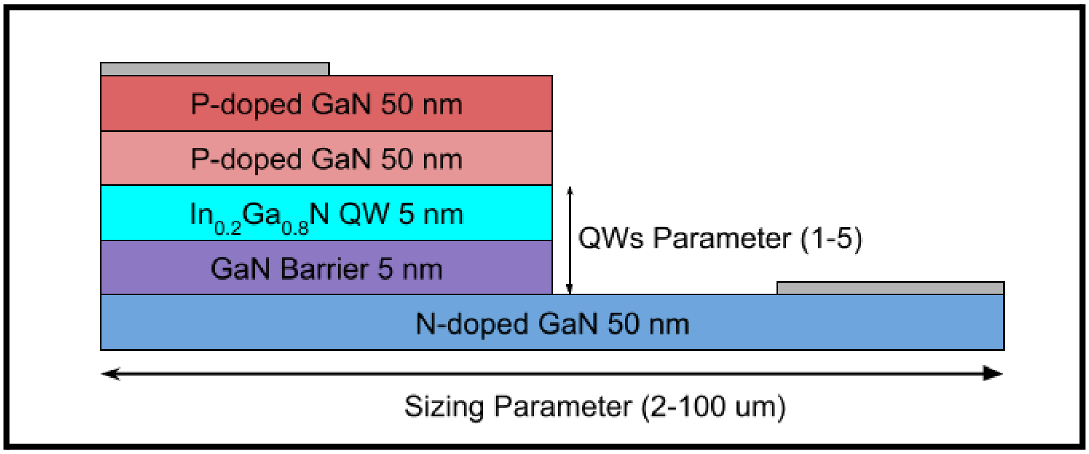

Figure 5: Micro LED structure used in simulation with size and QW parameters

Through some preliminary simulations of a two quantum well micro LED we can see the band structure of the device shown in figure 6 below. Looking at the energy gap between ground states in the quantum wells, it is roughly 2.5 eVs. This result is very close to the target value to get an emission wavelength of around 500 nm for blue light.

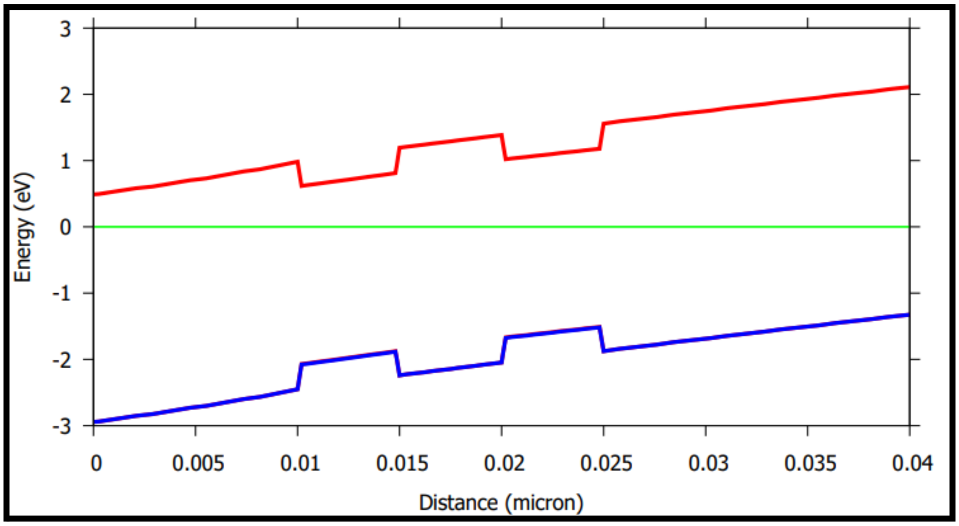

Figure 6: Band Structure of a two quantum well micro LED

Target Metric

In order to qualitatively understand the effect of quantum wells and sizing on the switching speeds of micro LEDs the metric this project will focus on is the rise and fall time of peak power output. The following simulation results have been obtained using the transient simulation functionality in APSYS Crosslight. Each parameterized structure is given an input voltage pulse with a rise and fall time, hold time, and hold voltage. Typically these values are 1 nS for the rise and fall times, 5-14 nS for hold time, and a hold voltage of 5V. The important output metrics is the rise and fall time of the resulting “Broad Area LED Total Power”, as this reflects the strength of the generated optical signal. An example of an input voltage pulse and resulting power output curve are shown below in figures 7 and 8.

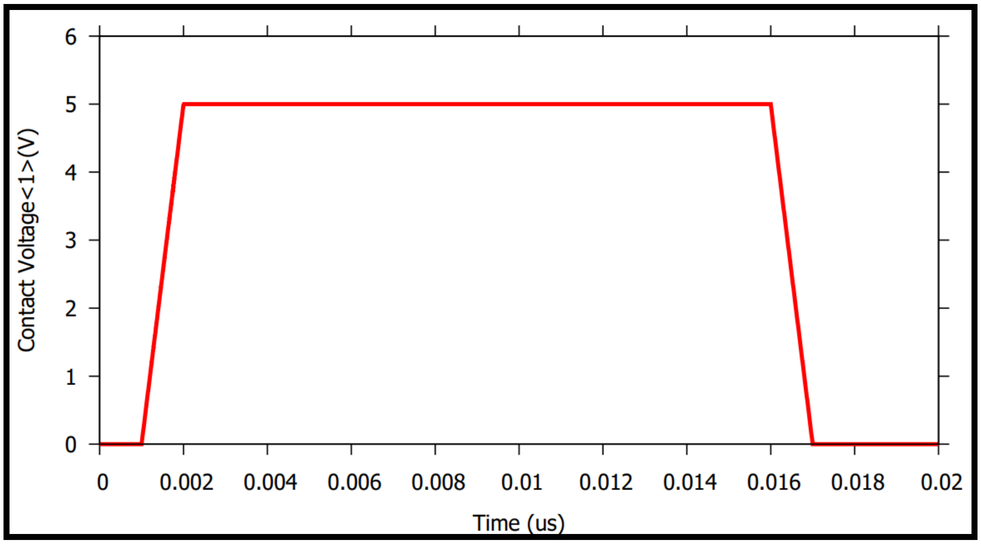

Figure 7: Example input voltage pulse to the micro LED

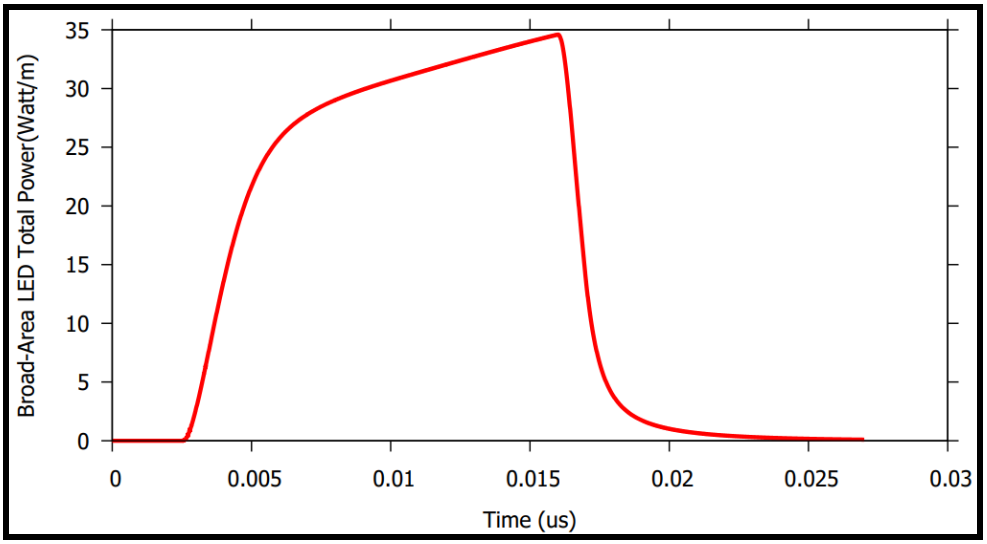

Figure 8: Example output power curve from the micro LED

Effects of Quantum Wells on Output Power Curves

The simulations on quantum well effects use two sizes of micro LED. The first sizing parameter being 30 um (fig 9), and the second being 2 um (fig 10). Both simulations used a transient input pulse of 5 volts and rise and fall times of 1 ns. The 2 um devices used a hold time of 4 ns, while the 30 um devices used a hold time of 14 ns. In both figures, as the number of quantum wells is increased there is a clear trend of the device taking longer to reach 70% of the maximum output power. The reason all trials appear to hit their peaks at similar times and decrease is due to the input voltage pulse turning off.

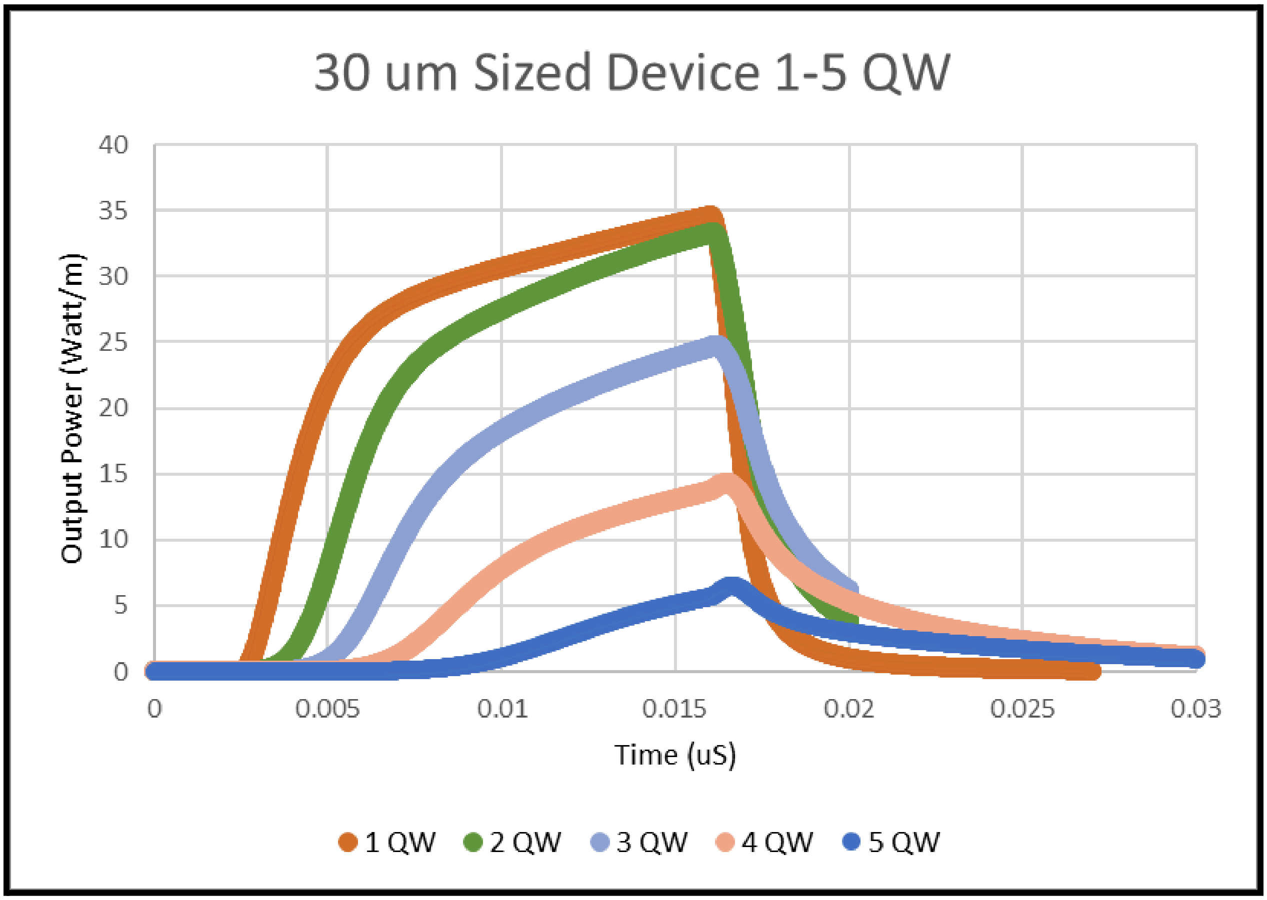

Figure 9: Output power as a function of time for 30 um sized device with 1-5 quantum wells

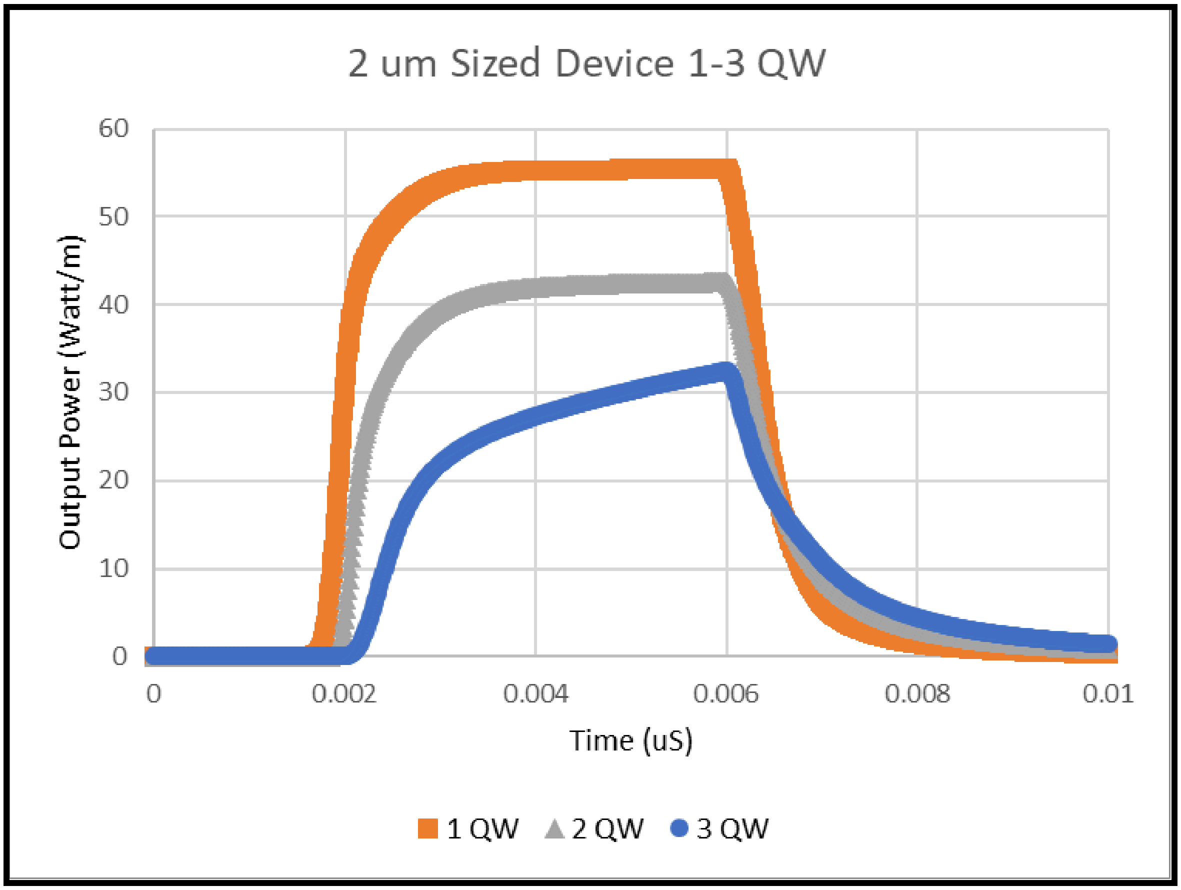

Figure 10: Output power as a function of time for 2 um sized device with 1-3 quantum wells

Numerically the time it takes each device to reach 70% of the maximum power output is tabulated in the following table. For these simulations each pulse begins at T = 1 ns.

70% Rise Times	**1 QW**	**2 QW**	**3 QW**	**4 QW**	**5 QW**
2 um Size	1 ns	1.3 ns	2.1 ns	NA	NA
30 um Size	3.5 ns	6.6 ns	8.5 ns	10.4 ns	13.1 ns

Table 1: Tabulated 70% response time for 2 um and 30 um devices (1-5 QWs)

Effects of Sizing on Output Power Curves

The following simulations are performed on micro LEDs with one quantum well, but with parameterized size as shown in figure 11. The sizes range from 2um to 30 um with a voltage input pulse of 5 volts, rise and fall times of 1 ns, and hold time of 4 ns.

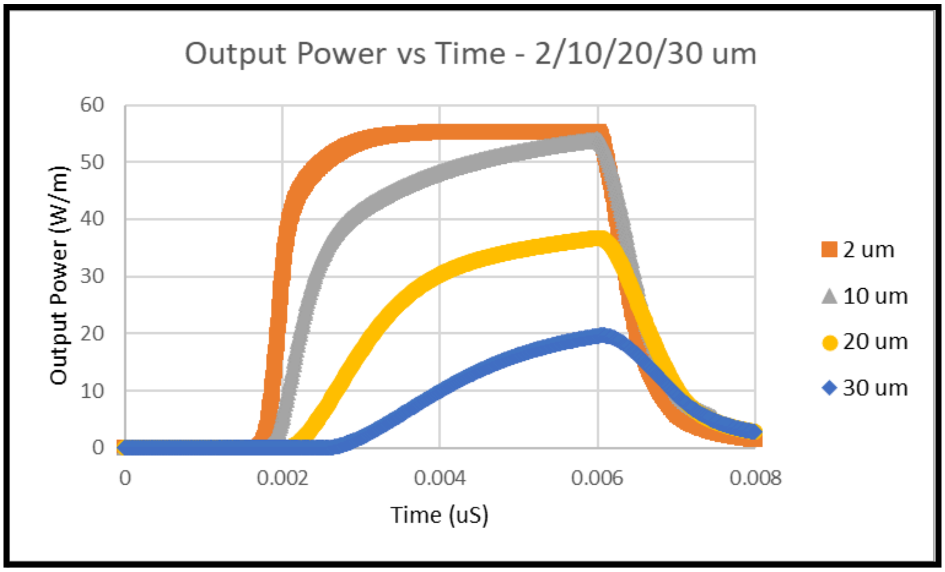

Figure 11: Output power curve from sizing comparison simulations

From figure 11 and table 2 there is a clear trend of increasing delay to reach 70% of the device’s max power as the sizing increases.

70% Rise Times	2 um Size	10 um Size	20 um Size	30 um Size
1 QW	1 ns	1.7 ns	2.5 ns	3.5 ns

Table 2: Tabulated 70% response time for 2 um and 30 um devices (1-5 QWs)

Discussion of Results

Looking at the graphs of the tabulated rise metrics in figure 12 below, we note that both the number of quantum wells and sizing of the micro LED have a negative linear relationship with the rise and fall times. In addition to understanding the impact of quantum wells and device sizing, it is important to consider the results in the broader LED design process. The observed trends show that increasing the number of quantum wells leads to longer response times, but have increased performance in other metrics. Namely internal quantum efficiency and droop are important metrics that need to be accounted for in order to achieve practical power efficiency. From the work of Yu Chieh Chiu [3], peak IQE is achieved at one quantum well, with a second maxima at three quantum wells. The issue with a one quantum well design is the efficiency droop effect caused by increased current densities causing charge overflow and increasing auger recombination effects. Additionally the trends found in this project encourage pushing for smaller device sizes, but there is another tradeoff of surface recombination that can significantly reduce efficiency as devices approach a couple micrometers. For a practical micro LED design for low power applications it would be best to choose three quantum wells and as large a size as possible to maximize efficiency. For a high frequency micro LED it would be best to choose one quantum well and minimize size to decrease transient rise times. These two examples are opposite ends of the design spectrum and for many applications a compromise must be made with the tradeoff between power efficiency and switching speed. Another design consideration is that low current/power micro LEDs will experience less efficiency. For designs where frequency is more of a concern and this condition is applicable, it may be more beneficial to use one quantum well.

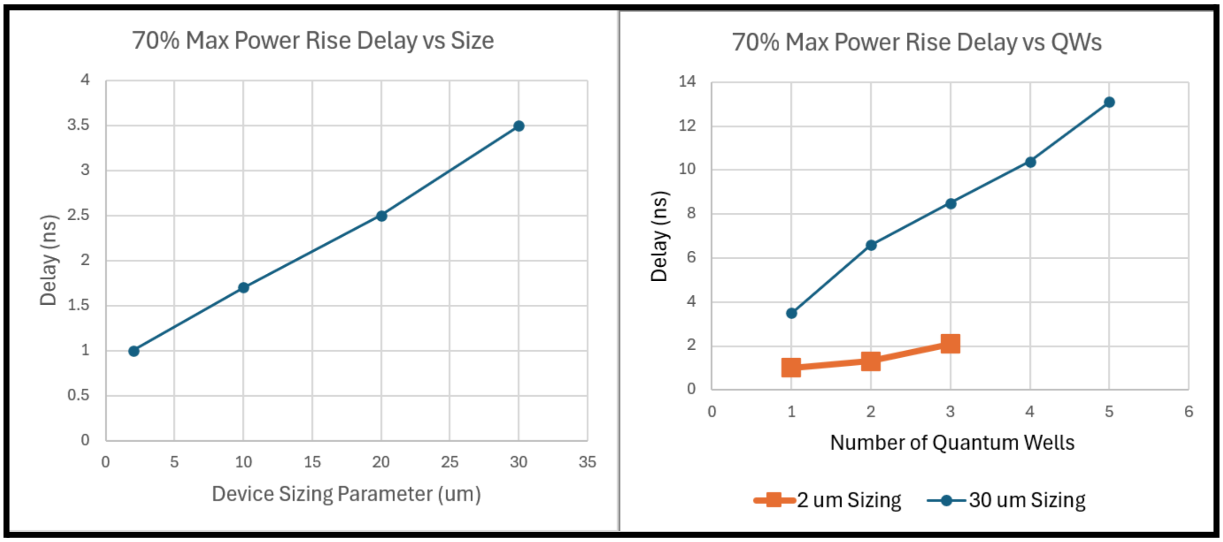

Figure 12: Delay to reach 70% of maximum power vs device size (left) and QWs (right)

Another metric that can offer a quantitative representation of performance incorporates both IQE and rise time delay is shown below, where Q is the quality of the micro LED. Below are the Q metrics for each simulation of differing sizings. Using this metric we can quantitatively compare various micro LED designs in their overall performance for optical interconnects.

$$Q = \frac{\eta_{IQE}}{\tau_{Rise}} \tag{3}$$

70% Rise Times	2 um Size	10 um Size	20 um Size	30 um Size
Q metric	0.18	0.26	0.22	0.16

Table 3: Relative Q metric for single quantum well at differing device sizings

Conclusion

With the growing demand for high-speed computation the necessity for efficient data transfer methods is increasing. Electrical interconnects are reaching their theoretical limits in many areas so other options with potential further improvement are needed. Optical interconnects, as an alternative to traditional electrical interconnects, offer the potential to significantly improve bandwidth, reduce power consumption, and reduce interference. This research project focuses on the design methods and tradeoffs in increasing the frequency bandwidth of micro LEDs used in data signal generation.

The findings of the simulations performed on single and multiple quantum wells and device sizes ranging from 2 um to 30 um gives insight into the tradeoffs when designing micro LEDs. The results indicate that while increasing the number of quantum wells offers enhanced power performance, it also leads to longer response times in terms of output power rise times. Conversely, reducing device size can further reduce transient rise times, while at the potential cost of surface recombination efficiency and further efficiency droop at higher current densities. These trade-offs necessitate a specific approach to micro LED design, where the specific requirements of each application must be weighed against performance metrics such as power efficiency and switching speed.

Furthermore, the research highlights the importance of considering broader design considerations such as efficiency droop and surface recombination effects when optimizing other metrics. The results of this project aim to show the advantages of optical interconnects as a way for improved computational speeds and reduced data transmission inefficiencies, ultimately contributing to power savings in high-speed processors and computing.

Moving forward, continued research in this field will be important for improving and understanding micro LED technology for optical interconnect applications. Further work is needed in demonstrating more detailed and accurate models and simulations to enable faster data transmission, reduced power consumption, and enhanced computational speeds. Additionally this report has solely focused on 500 nm wavelength blue light as one channel in a WDM system. The work done in this project will need to be applied to other materials and different wavelengths in order to fully maximize usage of the spectrum in data transmission. Integration of all the different materials, and designs with current semiconductor manufacturing technology will be the greatest challenge. It will require a strong foundation and understanding of each individual component to be commercializable and see widespread success.

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