

# Optical software defined radio transmitter extinction ratio enhancement with differential pulse carving

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## ABSTRACT

The purpose of this study is to investigate a new approach to the modulation of an optical signal which requires high extinction ratio (ER). A deep space, optical, pulse position modulated (PPM) link, may require an extinction ratio approaching 33 dB which is not easily achieved through the use of a single optical modulator. In a system where the slot clock is equal to the slot width, it is often not possible to meet ER requirements due to Inter Slot Interference (ISI). Furthermore, the high frequency ER of state of the art optical amplitude modulators is not large enough to allow for implementation losses. By using a second optical modulator in series with the first, it is possible to address both issues. A phase delay placed between each modulator allows for precision control of the pulse width, reducing ISI. The attenuation in the off slots combines linearly, reducing total extinction. Using this approach a series of 1 ns pulses were measured at a series of phase delays to approximate PPM pulses. These measurements were used to extrapolate the ER of a PPM signal at various PPM orders. An ER above 33 dB was observed for all PPM orders of 16 and above. At PPM 256 an ER of 48.2 dB was achieved.

**Keywords:** Inter Slot Interference, Extinction Ratio, Pulse Position Modulation, Optical Communication, Deep Space Communication

## 1. INTRODUCTION

A unique challenge in the development of a deep space optical software defined radio (SDR) transmitter is the optimization of the extinction ratio (ER). For a Mars to Earth optical link, an ER approaching 33dB<sup>1</sup> may be necessary. However, a high ER can be difficult to achieve at the low PPM orders and narrow slot widths required for high data rates. The quality of the digital signal transmitted by the SDR does not meet the amplitude and timing characteristics needed by an analog optical modulator. The conflicting implementation constraints of these two fundamentally different systems, the digital SDR and analog optical modulator, can make achieving the required ER very difficult. In this paper, the causes of fidelity loss at the interface between the SDR and optical modulator are discussed. The SDR signal quality requirements are derived and explored. It is shown that increasing the SDR signal quality enough to meet these requirements is impractical to implement due to bandwidth limitations of electronic components as well as Field Programmable Gate Array (FPGA) clock speed constraints. A novel optical modulation architecture based on low-voltage differential signaling and dual Mach-Zehnder Modulators (MZM) is presented which reduces the signal quality requirements on the SDR and increases the system ER.

The proposed electro-optic subsystem is used to interface a binary output Software Defined Radio (SDR) to optical transmission optics as part of an optical communications transmitter system. Traditionally, this task is accomplished through the use of a single MZM. MZM's are primarily analog components. In order to generate a high fidelity optical signal, the input electrical signal must be of equal high fidelity. Generating this signal electrically is a difficult task due to the competing requirements of digital components used in the SDR and the analog modulator. The waveform generated by the digital electrical and electronics engineering (EEE) components is imperfect and therefore degrades the Extinction Ratio (ER) of the optical signal. While these imperfections are too small to effect downstream digital system components, analog components will retain these imperfections. These imperfections include a non-ideal pulse shape caused by system bandwidth limitations, fundamental differences in the requirements of components used in digital systems and those designed for analog applications, interface standards mismatch, and timing jitter in both the transmitter and receiver.

The goal of the differential pulse carving process is to correct for imperfections in the electro-optic subsystem during modulation. This design relieves the SDR of the extreme fidelity requirements imposed by the optical modulator and allows for the pre-correction of jitter in the receiver. It simplifies the electrical portion which can significantly increase channel capacity and reduce size weight and power (SWaP).

## 2. BACKGROUND

### 2.1 Non-Ideal Signal Shape

One of the major contributors to ER degradation is the inability to generate an ideal PPM electrical signal. For a given average laser power and slot period, a square wave, correctly positioned, maximizes the energy within the signal slot and minimize the energy in the adjacent slots. However, in practice it is not possible to generate an ideal square wave due to the infinite bandwidth required. Any real pulse will have less than infinite bandwidth and will therefore be larger than the slot width. This forces unwanted signal energy into adjacent slots, which directly contributes to Inter-Slot Interference (ISI). This ISI contributes directly to the probability of a photon being detected in the wrong slot, contributing to bit errors.

Figure 1 shows the harmonics required in a pulse in order to achieve a specific extinction ratio in a fifty percent duty cycle signal. To produce this signal a sine wave was generated and odd harmonics were added to approximate a square wave. After the addition of each harmonic the theoretical light intensity of the trace was calculated using equation 1. Equation 1 is the transfer function of an ideal Mach-Zehnder modulators where  $V$  is the input potential, where  $I$  is the intensity and  $V_\pi$  is half-wave voltage of the modulator<sup>2</sup>.

$$I(V) = \sin^2\left(\frac{\pi V}{2 V_\pi}\right) \quad (1)$$

The extinction ratio was then calculated using equation 2 where  $t_1$  is the period where the slot is positioned,  $t_2$  is the period of off slots and  $N_{\text{slots}}$  is the number of non-signal slots. In this case  $N_{\text{slots}}$  is equal to one. This process was then repeated with the addition of each odd harmonic

$$ER = 10 \log_{10} \left( \frac{\int I(t_1) dt}{\int I(t_2) dt / N_{\text{slots}}} \right) \quad (2)$$

The trace shows that for a system where the pulse width is equal to the slot width, an extremely high system bandwidth is required to obtain ER design goal of 40 dB. For example, a system with a 1 ns slot width has a fundamental frequency of 1 GHz which would require harmonics up to approximately 800 GHz. This is not feasible to realize due to the bandwidth limitations of real components. Therefore, in order to achieve a high ER in a real system, the pulse width must be less than the slot width to correct for the finite bandwidth of the system.

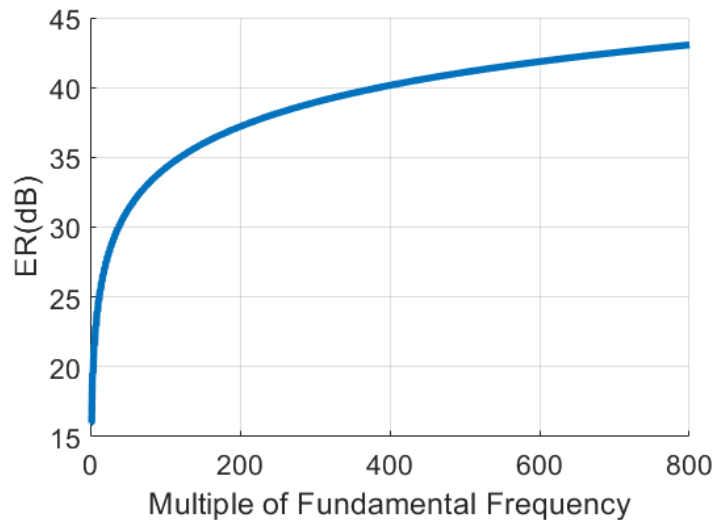


Figure 1. Possible extinction ratio given included odd harmonics of fundamental frequency

The reduction of the pulse width can be achieved via SDR implementation. However, in a system where the clock period is equal to the slot width, the clock speed must be at least doubled in order to shorten the pulse to half of the pulse width. It is also possible to triple the SDR clock speed, which offers a pulse width of one or two thirds slot width. Unfortunately, this offers very little control over the pulse width, while requiring the FPGA to operate at double the original clock speed which is often not possible.

## 2.2 Interfacing Digital and Analog components

The analog nature of the MZM causes other problems as well. The digital EEE parts required to generate a PPM signal at the required frequency do not interface well with an analog system. When designing a digital system the designers consider any potential below a certain threshold level ( $V_{IL}$ ) to be logic low. A digital signal therefore has a small range of values in which no unintentional bit flips occur. However, when these digital components are used to feed an MZM it is very difficult to pin the logic low signal to the null in the MZM transfer function. The logic low from the digital components is a range, and the MZM null is a point. Any deviation from the null point causes the desired destructive interference to misalign and some light gets through. Therefore it is not possible to optimize the MZM destructive interference that is being fed a signal from a digital component.

It is possible to solve this issue through the use of a Digital to Analog Converter (DAC). A DAC has many potentials available to the analog output. The output is also very well defined to a very strict tolerance. However a DAC is not ideal for PPM. PPM only requires two values, while DAC outputs offer many output potentials at the cost of increased complexity and cost. A DAC also requires much more power to run. For a spacecraft with limited resources, this is not an ideal trade.

## 2.3 Interface Standards

Another problem with the EEE parts available is the interface standards. Current state of the art components prefer to use Low Voltage Differential Signaling (LVDS). This standard uses two physical outputs for one signal. These signals have a common DC component and inverted data signals with respect to one another. However, Commercial Off the Shelf (COTS) MZM's and MZM drivers overwhelmingly utilize an unbalanced input. To the best of our knowledge there doesn't exist a solution to convert the LVDS signal to an unbalanced signal without a large loss in fidelity. As a result, we have been forced to terminate one of the LVDS lines and only use on half of the signal.

## 2.4 Jitter

Slot clock jitter is the effect of having a real clock signal that is not perfectly periodic. Any real system will exhibit this phenomena to some degree. In a PPM system, pulsed must be aligned to slots using a clock which contains some amount of jitter. Therefore the signal slots will display a jitter equal to that of the clock jitter. This causes the intended slot and the signal pulse to be slightly misaligned, forcing some signal energy into an adjacent slot, causing ISI.

## 3. SOLUTION ARCHITECTURE

The purpose of the proposed optical modulation subsystem is to relieve the SDR of the extreme signal quality requirements imposed by the use of an MZM. With the addition of a second MZM and a variable time delay, all of the imperfections in the electrical signal can be compensated for. The serialized nature of the design allows for an overall transfer function that pushes toward desired digital characteristics. This not only solves the problems caused by the use of digital components but also helps to removes noise and corrects for  $V_{IL}$ . The addition of a second MZM also allows for use of the second LVDS signal without the need for unbalancing. Finally, the proposed configuration allows the introduction of a time offset to the modulation of each MZM. This allows for precise control of the pulse width within the signal slot and optimization of ER and ISI for a given signal with various non-ideal characteristics and finite bandwidths.

The proposed subsystem, shown in Figure 2, utilizes two cascaded MZM's with an adjustable phase delay on the second MZM. In the design, a continuous wave (CW) laser is applied to the fiber optic input port of MZM 1. MZM 1 is modulated by the positive LVDS component of the PPM signal through a cable of a length that induces a time delay of  $\Delta 1$  (seconds). The output of MZM 1 is applied to the input of MZM 2 through a fiber of delay  $\Delta 2$ . MZM 2 is modulated by the negative LVDS component of the PPM signal through a cable of delay  $\Delta 3 + \Delta 4 + \Delta t$ . MZM 2 bias point is set to an inverting bias point to account for the inverted input signal. The system is designed such that when  $\Delta t = 0$ ,  $\Delta 1 + \Delta 2 = \Delta 3 + \Delta 4$ . This aligns the electrical and optical signals to recombine at MZM 2. As  $\Delta t$  is adjusted the optical and electrical PPM signals become misaligned. This causes the signal slot to be reduced in duration by the same length as  $\Delta t$ .

Both outputs from the SDR are used to drive their own individual MZM. By using all of the available signal, the quality of the signal transfer is increased. However, because LVDS is a balanced signal standard, the negative portion must be inverted in order to modulate correctly. Fortunately, the periodic nature of the MZM allows for this. By increasing or decreasing the MZM bias potential by  $V\pi/2$  the signal is effectively inverted. This inversion is much easier to accomplish than unbalancing and causes no loss in fidelity.

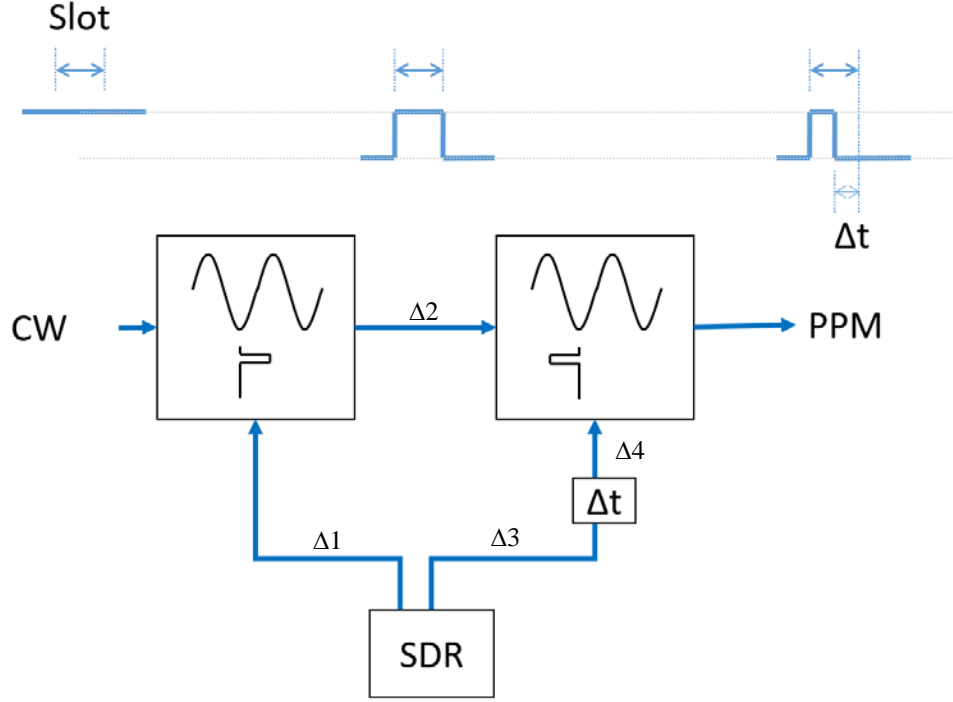


Figure 2. Cascaded Offset Optical Modulator Block Diagram

## 4. THEORY

### 4.1 More digital transfer curve

The ideal transfer function for this application would be a step function. A step function would allow a range of input potential that achieve a very precise binary valued output.

$$I_{\text{Ideal}}(V_{\text{PPM}}) = \begin{cases} 1, & 0 < V_{\text{PPM}} < \pi \\ 0, & \text{elsewhere} \end{cases} \quad (3)$$

Such a transfer function is not possible to build in practice due to the bandwidth constraints discussed earlier. However, the cascading of two MZM's changes the overall transfer function of the system toward something more helpful. This new transfer function is closer to the ideal than that of a single MZM. Applying the MZM transfer function equation to the system we obtain the following for the intensity output of MZM 1

$$I_{\text{MZM1}}(V_{\text{LVDS}_P}) = 1 * \sin^2\left(\frac{\pi V_{\text{LVDS}_P}}{2 V_{\pi}}\right) \quad (4)$$

To obtain the output for MZM 2 we must consider the non-continuous nature of the input light. The input is no longer a constant, continuous wave, but the modulated output from MZM 1. The intensity for the output of MZM 2 becomes:

$$I_{\text{MZM2}}(V_{\text{LVDS}_P}, V_{\text{LVDS}_N}) = I_{\text{MZM1}}(V_{\text{LVDS}_P}) * \sin^2\left(\frac{\pi V_{\text{LVDS}_N} + \Delta t}{2 V_{\pi}}\right) \quad (5)$$

The equation can be simplified if we consider the case where  $\Delta t = 0$ . Furthermore, accounting for the periodic nature of the MZM and assuming a properly biased system we can write:

$$V_{\text{LVDS}_P} = V_{\text{LVDS}_N} = V_{\text{PPM}} \quad (6)$$

$$I(V_{PPM}) = \sin^4\left(\frac{\pi}{2} \frac{V_{PPM}}{V_{\pi}}\right) \quad (7)$$

This result shows that the cascading of MZM's increases the order of the transfer function by two with the addition of each new modulator. A visualization of the impact can be seen in Figure 3. The range in which destructive interference occurs is dramatically expanded. This not only allows for lightening of the SDR signal quality requirements but also functions as filter for low amplitude signals which effectively filters noise. The impact of this noise filtering corrects for the  $V_{IL}$  of the SDR.

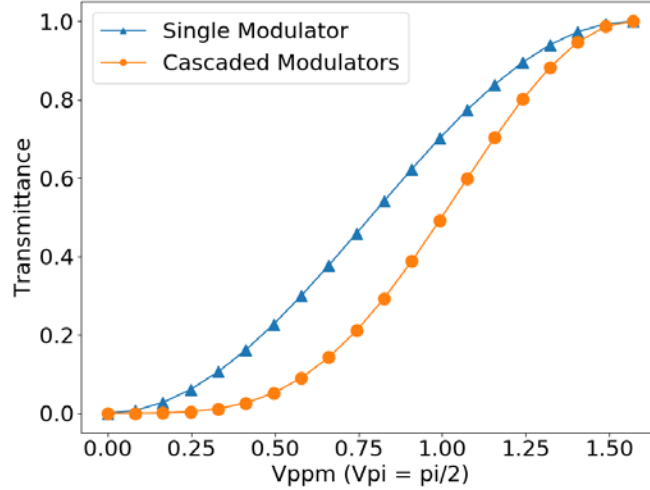


Figure 3. Transfer function to single and cascaded MZM configurations.

## 4.2 Pulse Shortening

An illustrative output is shown in Figure 4 which demonstrated the pulse shortening function. In this case the pulse width is 2 ns and the MZM's are 1 ns offset from each other. Each modulator is assumed to provide 30 dB of attenuation and no insertion loss. In the logarithmic scale the output pulse is a stair step shape. The signal peak appears where the pulses from MZM 1 and MZM 2 overlap. On both side of the peak signal area, there is a region where one MZM is attenuating and the other is not. This creates a step like structure on both sides of the pulse. It is in these stair step regions that the pulse carving takes place. Outside of these regions both MZM's are attenuating and the attenuation adds linearly. In this example a 2 ns electrical pulse has been shortened to 1 ns from the 1 ns offset between MZM's one and two. The shortening of the pulse and resulting reduction in ISI contributes significantly to an increase in ER.

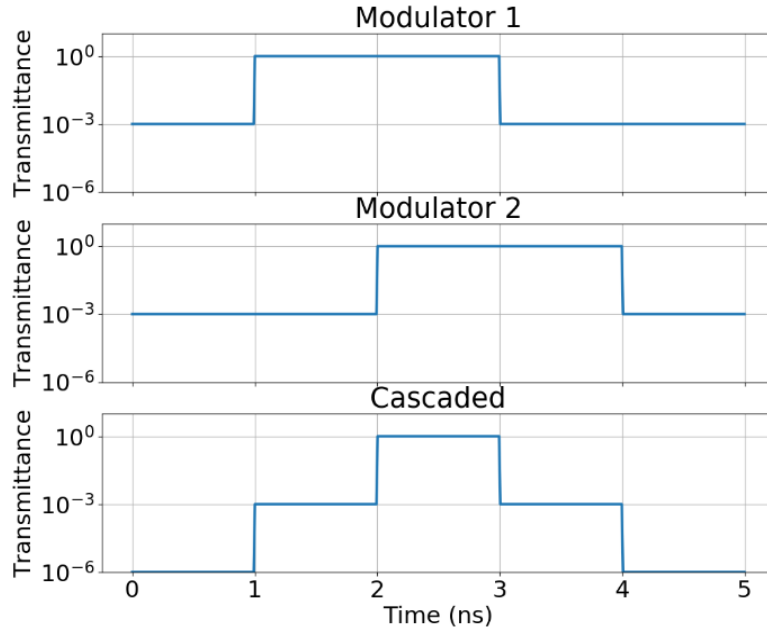


Figure 4. Serialization Timing Diagram.

## 5. TEST SETUP

A full system test of the cascaded offset optical modulator was conducted. Two separate MZM's were used with a capability of producing a DC ER of more than 40 dB. Each MZM was manually biased using a single SNSPD and a time-to-digital converter to count photon detection events. The time-to-digital converter was synchronized to the electrical pulse of MZM 1. A periodic signal with a constant duty cycle of 1:319 and a slot width of 1 ns was injected into the system. This is equivalent to a repeating PPM 256 signal. The intensity of the continuous wave laser input was attenuated with a fiber optic attenuator in order to allow for the use of a single channel SNSPD. An input of higher intensity would require multiple detections per pulse. These photons would be missed on a single channel, however the noise would still be counted. This attenuation being disproportional to slot photons would therefore provide an inaccurate measurement at high powers. The time-to-digital converter was set to record a histogram over 1 period at a resolution of 100 ps per bin. A measurement with the laser off was taken to determine the dark count rate of the SNSPD. Histogram of photon counts were recorded at a series of eight different offsets. The mean dark count was subtracted from each bin to correct for measurement noise. The measurement was not corrected for detector jitter.

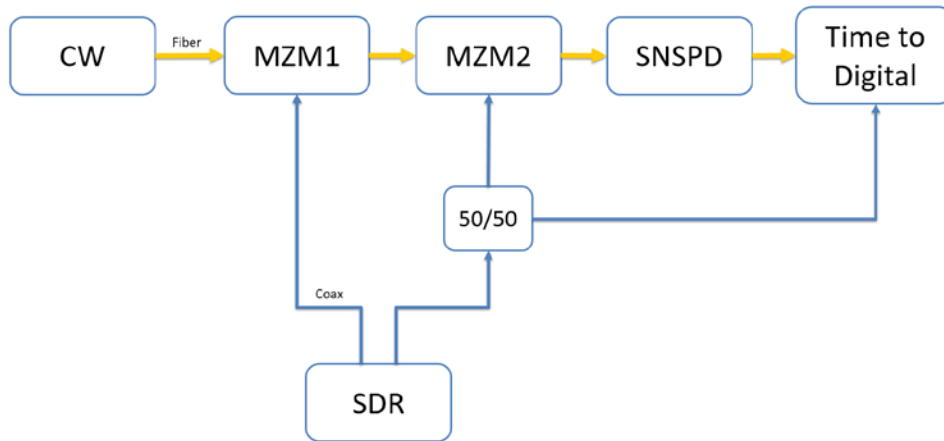


Figure 5. Test Setup

## 6. RESULTS

### 6.1 Discussion

Figure 5 shows the histogram for the series of offsets. The offsets are labeled by the offset setting of the delay module and not the overall offset of the MZM's. This can be seen by the evident stair step formation at zero offset. For context, this same plot is provided in linear scale in Figure 6. Each MZM appears to be providing approximately 30 dB of attenuation. The impact of the offset carving can be clearly seen on the edges formed by MZM 2. The offset is seen here because the time-to-digital instrument is synchronized to MZM 1. It is clearer in the linear scale that the pulses have been shortened enough to contain most of the energy within a 1 ns slot.

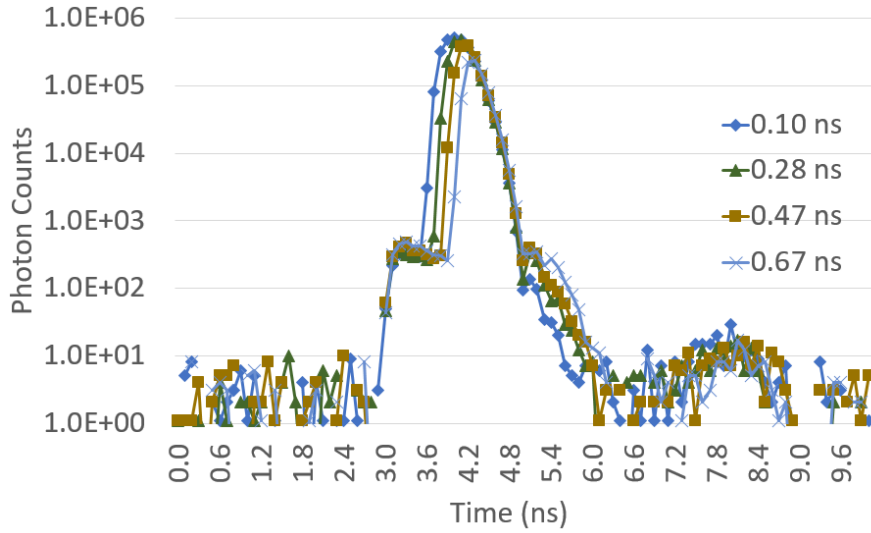


Figure 6. Histogram of photon counts in logarithmic scale

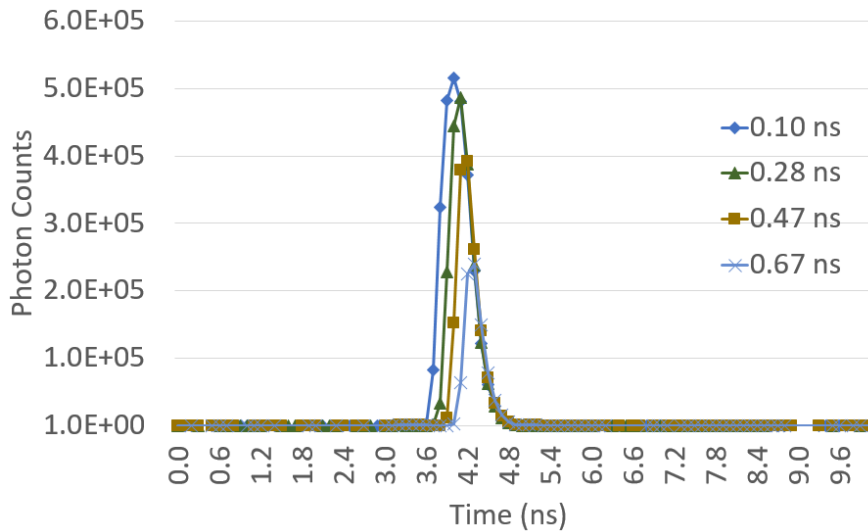


Figure 7. Histogram of photon counts in linear scale



Table 1. FWHM of carved pulses

(ns)	0.10 ns	0.29 ns	0.48 ns	0.67 ns
FWHM	505	390	330	300

To determine the ER for each offset the slot phase must be determined. This function is usually reserved for the SDR receiver which must recover the clock in order to decode the signal. In this case, each histogram was correlated with an ideal pulse to determine the phase of maximum correlation. Using this slot positioning  $t_1$  and  $t_2$  were determined and equation 2 was used to calculate the ER for each offset. To determine the ER potential for lower order PPM signals, the unused off bits were removed from the calculation. The off bit before and after the slot were included in the calculation in order to include all ISI. The resultant ER for PPM orders at each offset in the recorded series. Is shown in table 2.

Table 2. Extrapolated ER potential of pulses for a series of offsets.

(dB)	0.0 ns	0.10 ns	0.19 ns	0.29 ns	0.38 ns	0.48 ns	0.57 ns	0.67 ns
PPM 4	28.4	30.5	28.0	32.5	30.3	31.1	29.3	27.9
PPM 16	35.1	37.0	34.8	39.1	37.0	37.6	36.0	34.6
PPM 32	38.1	39.8	37.7	41.6	39.8	40.3	38.8	37.5
PPM 64	40.4	41.9	40.2	43.3	41.9	42.4	41.1	40.0
PPM 128	43.2	44.5	43.0	45.8	44.6	45.0	43.8	42.7
PPM 256	45.9	47.1	45.7	48.2	47.2	47.5	46.4	45.2

## 7. SUMMARY

In conclusion, modulating a signal for optical transmission imposes unique challenges. It was shown that a single MZM cannot reach the design goal of 40 dB ER when driven by a real system where the pulse width and slot width are equal. Among the other challenges at this interface are the fundamental difference between the function of digital components and the ER requirements of an analog optical modulator, both in amplitude and in time. The optical modulation subsystem proposed here address all of these challenges, at the cost of increased complexity and additional insertion loss. Measurement and analysis of the system showed that for a 1 ns pulse width, a 40 dB ER was achieved for PPM orders above 32. This ER should meet the needs of a deep space optical transmitter.

## 8. ACKNOWLEDGMENTS

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