Transmitter Optimization for PAM4 Signals

THORLABS
APPLICATION NOTE

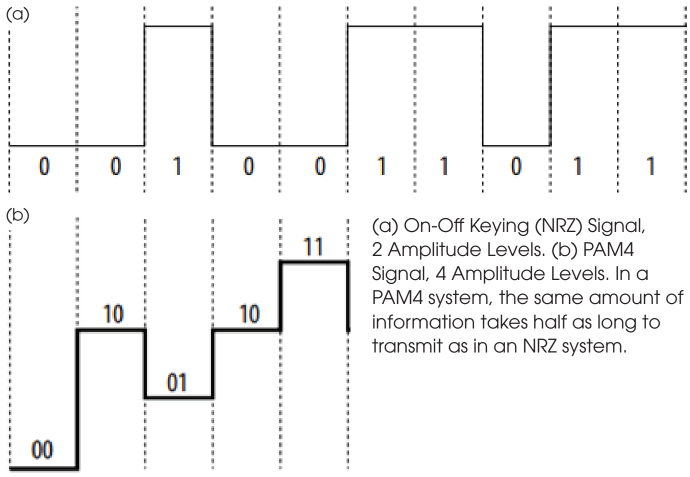
OVERVIEW

PAM4 is a modulation format where four amplitude levels are present. The acronym stands for Pulse Amplitude Modulation, 4 Levels.

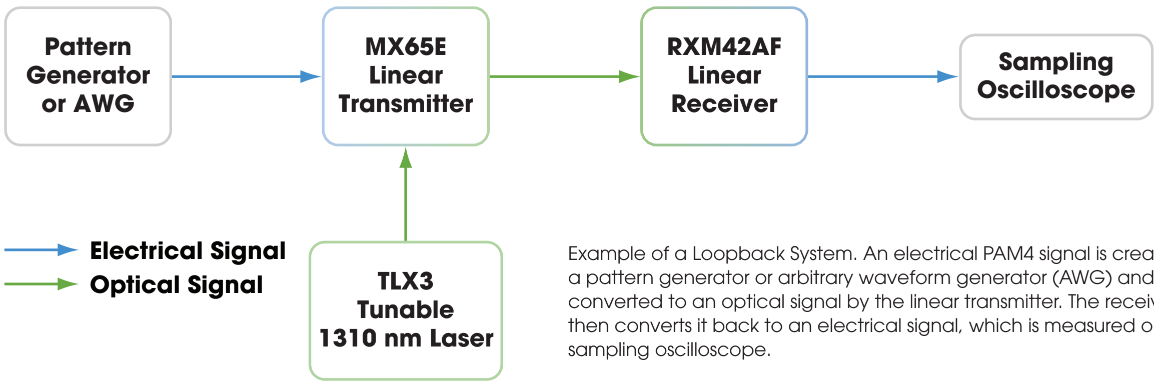
In typical digital signals, information is transmitted as a series of 1s and 0s. In an optical system, this means that light is either present or absent. PAM4 is different from traditional on-off signaling, as the amplitude of the signal can be one of four different levels.

Using PAM4 allows twice as much information to be transmitted in a given period of time, but adds a requirement that all elements in the system must be linear. Described another way, twice the information can be transmitted using the same 3 dB system bandwidth.

Optimizing the response of a PAM4 system requires careful consideration of linearity at each stage, as a well as the optimization of several system parameters.



(a) On-Off Keying (NRZ) Signal, 2 Amplitude Levels. (b) PAM4 Signal, 4 Amplitude Levels. In a PAM4 system, the same amount of information takes half as long to transmit as in an NRZ system.



Example of a Loopback System. An electrical PAM4 signal is created by a pattern generator or arbitrary waveform generator (AWG) and then converted to an optical signal by the linear transmitter. The receiver then converts it back to an electrical signal, which is measured on a sampling oscilloscope.

IMPORTANT CONCEPTS

Linearity

For standard on-off keying, also known as Not Return to Zero (NRZ), the primary consideration is making sure that a signal is clearly identified as either on or off. One way to accomplish this is to use very high gain components which force all signals to become equal to 1 (on) or 0 (off). However, for PAM4 signals, intermediate amplitudes must be preserved by all elements in the system so that all four levels are present in the output of the system.

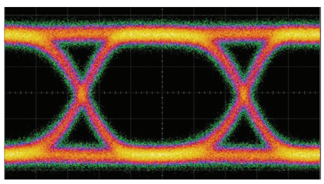
Bits and Bauds

Bit rate and baud rate are similar but separate concepts when describing PAM4 signals. Bit rate describes the total information communicated in a period of time. In contrast, baud rate describes how many symbols are communicated in a period of time, where each symbol may contain one or more bits of information. In an on-off keying system, each symbol is either a 1 or a 0, and thus contains one bit. In a PAM4 system, each symbol contains two bits for a total of four possible values: 00, 01, 10, or 11.

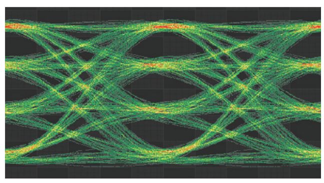
Eye Diagrams

An eye diagram is a diagnostic tool used to evaluate the quality of a signal. It can be used to simultaneously evaluate:

- Amplitude noise – on the vertical axis
- Timing jitter – on the horizontal axis
- Linearity – based on the vertical spacing of the amplitude levels
- Bandwidth – based on the rise and fall times of transitions between levels



2-Level (On-Off Keying) Eye Diagram



4-Level (PAM4) Eye Diagram

TRANSMITTER BIAS SETTINGS

The MZM modulator in Thorlabs' MX Series Reference Transmitters has a sinusoidal response to voltage. While amplitude and spacing remain constant over time, the phase of the signal shifts over time and temperature. This change over time requires the use of a closed-loop feedback system to ensure optimal long-term performance.

Multiple methods can be used to determine the optimal bias point and then maintain operation at that point. These different modes of operation are discussed in the individual product manuals for the MX family of instruments. However, there are special considerations when operating with a PAM4 signal, which are described below.

The dither method for identifying the quadrature point is very effective at identifying the optimal bias point for operation. However, use of the electrical dither tone adds noise to the signal. In the case of PAM4 signals specifically, this optical amplitude dither results in significant noise in the eye diagram. Fortunately, the MX family of transmitter instruments have an alternate mode of operation which can be used to maintain bias in a closed-loop arrangement without introducing noise on the signal. This mode of operation is known as Constant Ratio bias mode. To the right are instructions for entering this mode of operation, which are slightly different between the front panel and remote control settings.

Front-Panel Control for Constant Ratio Mode

1. Turn the instrument on. All major control groups should be on: Laser (if present), VOA, AMP (if present), and BIAS.
2. Choose the QUAD bias mode.
3. Wait for the green indicator light to stop blinking (indicating that the bias is locked at quadrature), then wait an additional 5 seconds.
4. Change the bias mode to Constant Ratio: press MAN to select Manual mode, then select Constant Ratio in the HOLD section.

Remote-Control Constant Ratio Mode

1. Turn the instrument on. All major control groups should be on: Laser (if present), VOA, AMP (if present), and BIAS.
2. Choose the QUAD bias mode (MZM:MODE:3).
3. Wait for the system to stabilize (MZM:SETpoint? returns a 1), then wait an additional 5 seconds.
4. Measure the power at Tap 1 (LASER:TAP:MW?).
5. Measure the power at Tap 2 (MZM:TAP:MW?).
6. Calculate the ratio of power between Tap 1 and Tap 2.
7. Set the device to Constant Ratio mode and set the ratio to the value calculated in the previous step (MZM:MODE: 8 , MZM:HOLD:Ratio: (calculated value)).

Note: if there is any change in the wavelength or pattern duty cycle, the above steps will need to be repeated.

MODULATOR TRANSFER FUNCTION

The transfer function of the modulator is a sinusoid. Because of this, its response is inherently nonlinear. However, there are multiple techniques which can be used to achieve both a high extinction ratio and equally spaced levels.

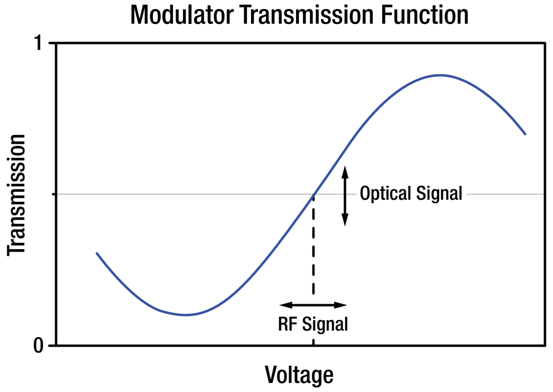
Below is an example plot of optical intensity vs. applied RF voltage which will be referenced in the following sections.

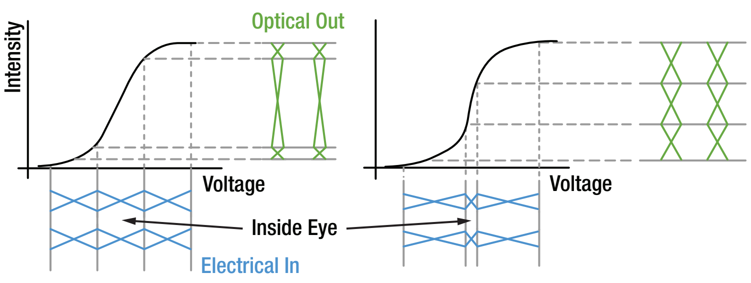
Inside/Outside Eye Adjustment

One simple method to achieve a good extinction ratio with equally spaced levels in a PAM4 optical signal is by adjusting the relative amplitudes of the "Inside Eye" vs. "Outside Eye". This adjustment takes place in the pattern generator, and terminology changes between vendors. Below is a graphic showing how reducing the amplitude of the "Inside Eye" results in an improvement in spacing between the levels.

Advanced Modulator Linearization

Many pattern generators and AWGs offer more advanced methods for improving the spacing between levels in PAM4 eye diagrams. One method is by using a multi-tap equalizer incorporated into the transmitter. Another is by advanced functions within an AWG which perform a linearization computation optimized to the modulation transfer function. Both options are highly dependent on the transmitter hardware and software used, and it is recommended to discuss them with applications support for whatever pattern generator or AWG is used in a specific test setup.





Changing the input voltage pattern can achieve equally spaced optical output levels and thus a "clean" PAM4 signal.

MODULATION DEPTH AND LINEARITY

As discussed in the previous section, the transmission function of the MZM modulator is not linear, but a sinusoid. This results in a trade-off between modulation depth and linearity. The above section describes how to mitigate this issue when using PAM4 signals specifically. This section discusses the issue more generally and presents the trade-offs associated with generic signal types.

Modulation Depth and Linearity vs. Input Swing

Modulation depth is a non-linear function of the input swing seen by the modulator. Higher input swings result in greater modulation depth, but more non-linearity.

As the signal level increases, modulation depth increases, but so does non-linearity, or total harmonic distortion (THD). The plot to the right shows this relationship for the MX65E linear reference transmitter. Note that the input swing levels are a small fraction of V_{pi} because this instrument uses an RF amplifier with a gain of ~11 dB, or ~3.5 V/V.

RF Amplifier Types and Gain

Applying the correct signal level to the modulator is important for proper operation of the transmitter, and the signal level used depends on the application.

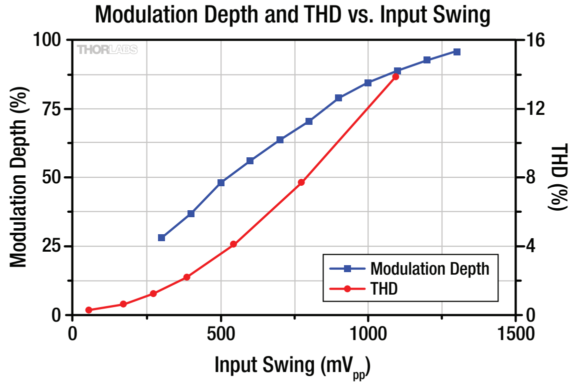
For the case where linearity is the dominant factor, such as for swept-sine analysis, smaller amplitudes are required. For these small signals, the modulator behaves very linearly. In our MXxxG family of calibrated EO transmitters, no amplifier is included to keep signals in this linear range.

When modulation depth is the main consideration, an amplifier with a very large gain which clips the signal at exactly the V_{pi} of the modulator is desired. This type of amplifier is known as a limiting amplifier and is used in our MXxxB family of products targeted for NRZ applications.

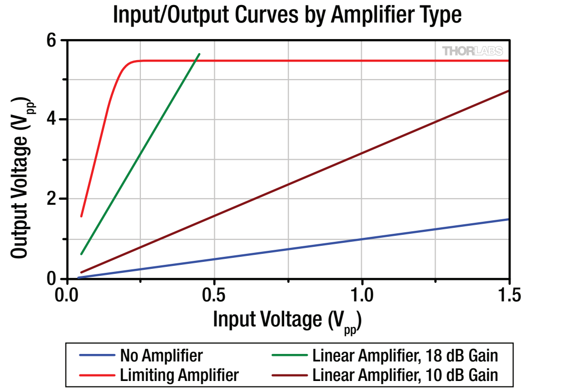
When both modulation depth and linearity matter, a linear amplifier must be used. These amplifiers typically have a low to moderate level of gain, and their gain is sometimes adjustable. The main purpose of these amplifiers is to ensure that the signal levels present at the output of pattern generators and AWGs can be amplified to a reasonable percentage of V_{pi}. These amplifiers are typically used in combination with appropriate pre-conditioning of the signal to overcome any non-linearities present as a result of signals which are a large percentage of V_{pi}.

In the case of our MX35E and MX35D transmitters, a linear amplifier with adjustable gain is used. Because the gain of the amplifier is adjustable, it can accommodate a wider range of input signal amplitudes while maintaining an optimal output signal amplitude.

Modulation Depth and THD vs. Input Swing



Input/Output Curves by Amplifier Type



FREQUENCY RESPONSE – MINIMIZING LOSS AND COMPENSATION

The above sections have emphasized the importance of the final levels of each of the four signal levels in the PAM4 eye diagram. In addition to the final signal level, frequency response, or how the optical waveform moves from one level to another, is also important.

Sufficient bandwidth is required to move from one signal level to another in a small fraction of the symbol length – if it takes too long to transition from a low level to a high level, the eye diagram will close. At high baud rates, many different elements in the signal path can reduce bandwidth.

It is important to maintain bandwidth throughout the system, and if possible, to compensate for high-frequency loss where present.

Cable Loss

Cable loss is an important consideration in high-speed systems. Even a 1-foot length of low-loss cable introduces 1.5 dB of loss at 40 GHz, so keeping electrical cable length to a minimum is important in maintaining the fidelity of high-frequency signals.

Equalization and Compensation

Many transmitters and oscilloscopes can compensate for high-frequency roll-off in frequency response. This can be achieved using a variety of techniques. Some systems use a multi-tap equalization system to correct for frequency response in the system. Others can characterize the frequency response of the whole system, then mathematically correct based on the measured results. Still others allow the user to compensate for a known frequency response by loading a de-embedding file which contains the measured response of different elements in the system.

It is common when characterizing a receiver, for example, to de-embed the response of the transmitter and cables in the system, so only the response of the device being testing is measured. S2P files characterizing the frequency response of Thorlabs' MX65E transmitters are available by contacting Tech Support.