# QAM Receiver

## 1 OBJECTIVE

Build a coherent receiver based on the 90 degree optical hybrid and further investigate the QAM format.

## 2 PRE-LAB

In the Modulation Formats – QAM Transmitters laboratory, a method of encoding data onto the amplitude and phase of the electric field was demonstrated. However, to extract this modulated signal from the optical signal a different detection scheme is required since photodetectors only capture the power of the incident field and not the phase. Previously, the electric field was found at the output of the Mach-Zehnder Modulators (MZMs) to be:

$$\boldsymbol{E_{out}}(t) = -\boldsymbol{E_{in}} \sin\frac{\pi V_1(t)}{V_\pi} e^{j\omega t}. \tag{1}$$

The secondary MZM used to modulate the quadrature phase carrier produces a phase shifted version:

$$\boldsymbol{E_{out}}(t) = j\boldsymbol{E_{in}} \sin\frac{\pi V_2(t)}{V_\pi} e^{j\omega t}. \tag{2}$$

### 2.1 COHERENT DETECTION WITH 90-DEGREE OPTICAL HYBRID

The method for retrieving the two signals $V_1(t)$ and $V_2(t)$ involves a continuous wave laser (called the local oscillator) and four photodiodes. The scheme is presented below in Figure 1.

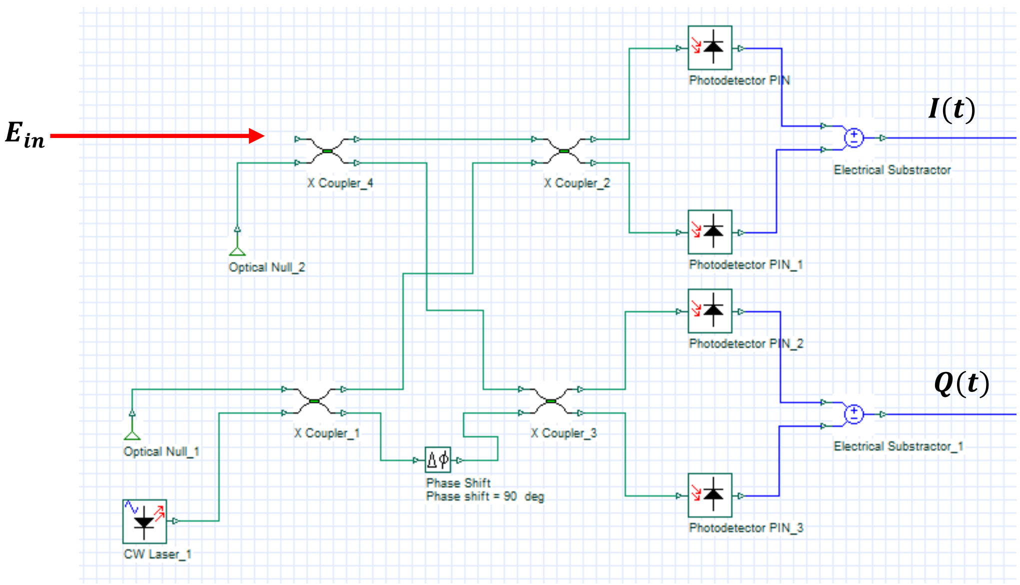


*Figure 1: A 90-degree optical hybrid used to extract the electrical signals.*

Before calculating the output of the detector, the transfer functions of the cross coupler and photodetectors needs to be known. First the electric fields at the output of the cross couplers is related to the input by:

$$\begin{bmatrix} \boldsymbol{E_{out_1}} \\ \boldsymbol{E_{out_2}} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -j \\ -j & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{E_{in_1}} \\ \boldsymbol{E_{in_2}} \end{bmatrix}. \quad (3)$$

Ignoring some constants, the current produced at the output of a photodetector is:

$$\boldsymbol{I_{out}} = |\boldsymbol{E_{in}}|^2 = \boldsymbol{E_{in}} \cdot \boldsymbol{E_{in}}^*. \quad (4)$$

<u>Questions:</u>

2.1.1 Assuming the local oscillator can be represented by $\boldsymbol{E_{LO}} e^{j\omega t}$ and the transmitted optical signal is $\boldsymbol{E_{signal}}(t) = -\boldsymbol{E_{in}} \sin\frac{\pi V_1(t)}{V_\pi} e^{j\omega t} + j\boldsymbol{E_{in}} \sin\frac{\pi V_2(t)}{V_\pi} e^{j\omega t}$, find the detected signal before each of the four photodetectors.

2.1.2 Using these four representations of the field, find the currents at the output of the photodetectors and finally the main two current resulting from the subtraction.

2.1.3 For small voltages, the expressions for output current found above are approximately linear. However, for large voltages the linearity is loss. How should the signal be pre-distorted to regain the linearity?

# 3 Coherent Communication System

## 3.1 Back to Back System

The most basic and ideal situation of a coherent system is a modulator followed directly by a demodulator without any actual transmission link in between. Such a set up minimizes the sources of noise and distortion inherent in communication systems. Starting first with this basic setup is an important first step to not only confirm that a communication scheme is working, but also to tweak parameters to minimize sources of distortion in the modulator and demodulator. Build the 16 QAM back to back system shown in Figure 2 from the list of components:

| | |
|---|---|
| • BER Test Set | Test Sets/Binary |
| • QAM Sequence Generator | Transmitters Library/Coders |
| • M-ary Pulse Generator | Transmitters Library/Pulse Generators/Electrical |
| • CW Laser | Transmitters Library/Optical Sources |
| • LiNb Mach-Zehnder Modulator | Transmitters Library/Modulators/Optical |
| • Electrical Gain | Signal Processing/Arithmetic/Electrical |
| • Electrical Bias | Signal Processing/Arithmetic/Electrical |
| • Electrical Subtractor | Signal Processing Library/Arithmetic/Electrical |
| • Phase Shift | Passives Library/Optical |
| • X Coupler | Passives Library/Optical/Couplers |

| | |
|---|---|
| • PIN Photodiode | Receivers Library/PIN Photodiode |
| • QAM Sequence Decoder | Receivers Library/Decoder |
| • Decision | Receivers Library/Demodulators |
| • Fork | Tools Library |

## Component Properties

| | |
|---|---|
| **BER Test Set** | |
| Number of leading zeros | 32 |
| Number of trailing zeros | 32 |
| Polarization Type | Single |
| **CW Laser** | |
| Linewidth | 0.1 MHz |
| Generate random seed | Disabled |
| **LiNb Mach-Zehnder Modulator** | |
| Extinction Ratio | 25 dB |
| Switching bias voltage | 3 V |
| Switching RF voltage | 3 V |
| Insertion Loss | 1 dB |
| **Phase Shift** | |
| Phase shift | 90 degrees |
| **X Coupler** | |
| Additional Loss | 1 dB |
| **PIN Photodiode** | |
| Noise calculation type | Numerical – Convert noise bins |
| **Decision** | |
| Polarization Type | Single |
| Modulation Format | 16QAM |
| DC Blocking | Enabled |
| Normalize | Enabled |

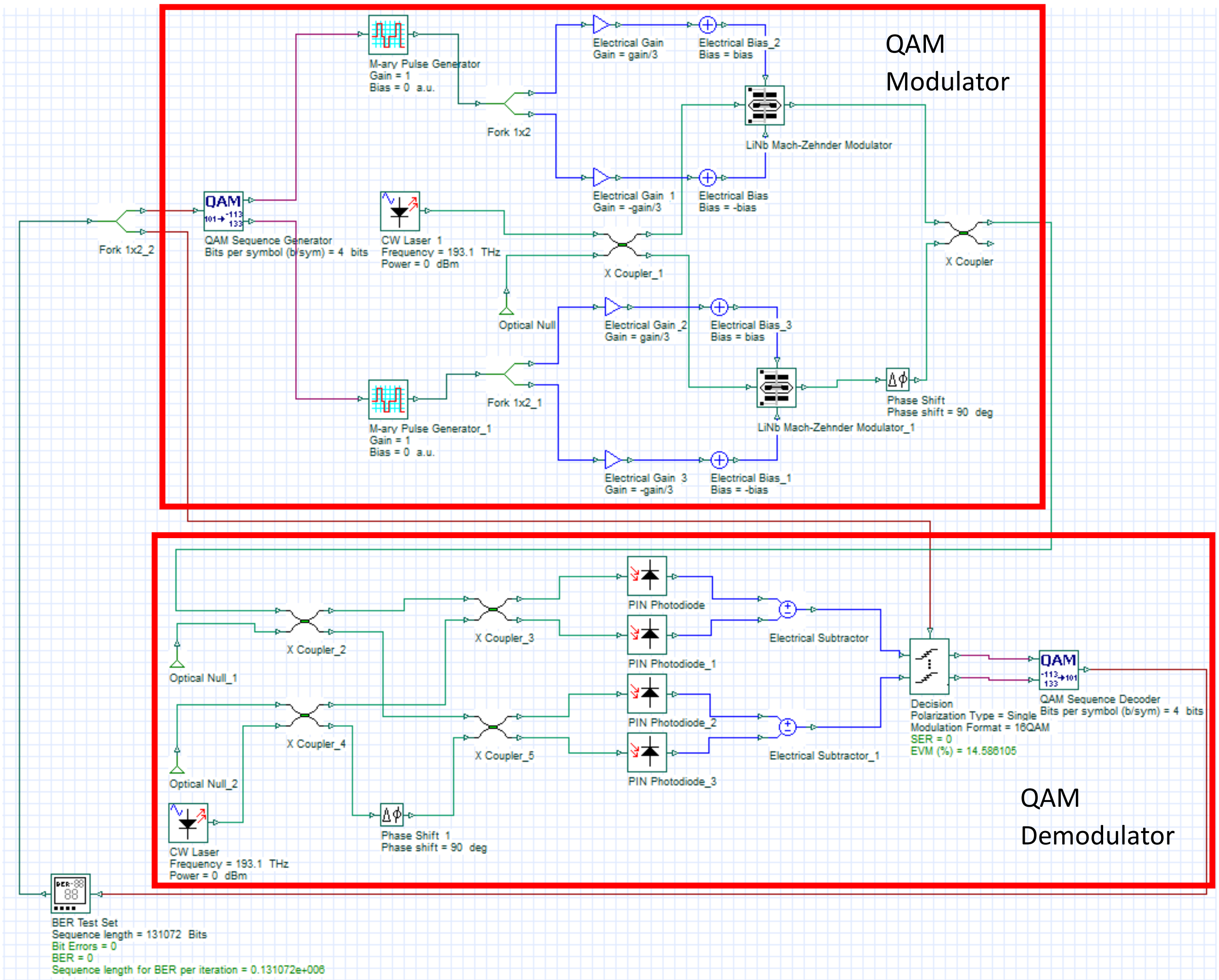


*Figure 2: A back to back 16 QAM system consisting of a quadrature modulator and a coherent receiver making use of a 90 degree optical hybrid.*

<u>Questions:</u>

3.1.1 Set the electrical bias to ±1.5 V and electrical gain to ±0.32 for the top and bottom arms of the MZMs. Place a constellation visualizer after the Electrical Subtractors to confirm the correct constellation of 16 QAM. To achieve a full constellation the Sequence length may need to be increased, so that the chances of generating all the possible symbols is greater.

3.1.2 This coherent receiver design is in fact unrealistic. The receiver design relies on the fact that the local oscillator has the same phase as the transmitter laser, but unless the same exact laser is used there will be a random difference in phase between the two lasers. Run the simulation again but set the local oscillator laser to generate a random seed in the component properties. Describe the constellation diagram.

3.1.3 Return the CW Lasers to the initial parameters, where they each have the same random seed of 0. As shown in the pre lab the detected electrical signals are not the exact input voltages. For a suitably long bit sequence length plot the BER as a function of the electrical gain starting from 0.5 and ending at 0.1. Explain why the gain effects the BER as it does.

## 3.2 QAM Spectral Efficiency

The ideal QAM transmitter creates a perfect constellation diagram with no distortion introduced from the MZMs or the random phase from the continuous wave laser. One of the main benefits of a QAM transmission format is that the spectral range is used more efficiently. This can be seen qualitatively from the fact that the symbol periods of a 4 QAM system are twice as long as the bit periods of an On-Off Keying format, which means you need roughly half the signal bandwidth.

The spectral efficiency gives a measure of how many bits per second can be transmitted per Hertz of bandwidth used. The expression for spectral efficiency is given by Equation 5.

$$Spectral\ Efficiency = \frac{Gross\ Bit\ Rate}{Signal\ Bandwidth} \tag{5}$$

For many types of signals the bandwidth can be difficult to give an exact value and that is because the Fourier transform of rectangular pulses gives a sine cardinal shape to the frequencies amplitudes. Although the frequencies drop in amplitude as they get larger, discarding the higher frequencies can distort the time domain signal. Simpler modulation formats like NRZ allow for simply filtering out the higher frequencies, for example the signal below can filtered out to leave only the first hump. This translates to a signal bandwidth of 10 GHz.

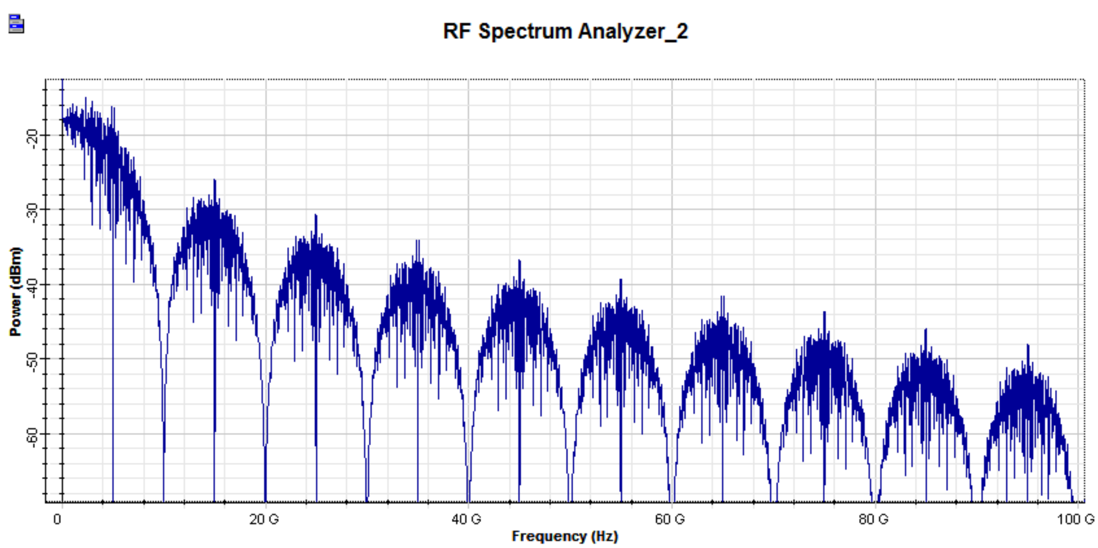


*Figure 3: Power spectrum of detected 10 Gbps NRZ format.*

If the same trick is applied to a modulation such as 16 QAM, the signal will be heavily distorted and the decision component will have a hard time decoding the proper symbols. However, instead of using an M-ary Pulse Generator in the modulator, which generates multilevel rectangular pulses, a pulse which has a frequency limited property can be employed. In fact the answer is shown in Figure 3! If the rough signal shape of Figure 3 is used as the time domain pulse, the Fourier transform will be constrained within the low frequencies. The M-ary Raised Cosine Pulse Generator is the exact component that can be used to create this type of signal. The raised cosine pulse overlaps with adjacent bits and can cause errors near the beginning and end of the bit sequence. For this reason, the first and last few bits are ignored from the sequence and are called guard bits.

The frequency domain signal in Figure 4 is tightly confined to frequencies less than 10 GHz. It is much clearer in this case that the signal bandwidth is indeed 10 GHz. Thus, the spectral efficiency of this format is 1 (bit/s)/Hz.

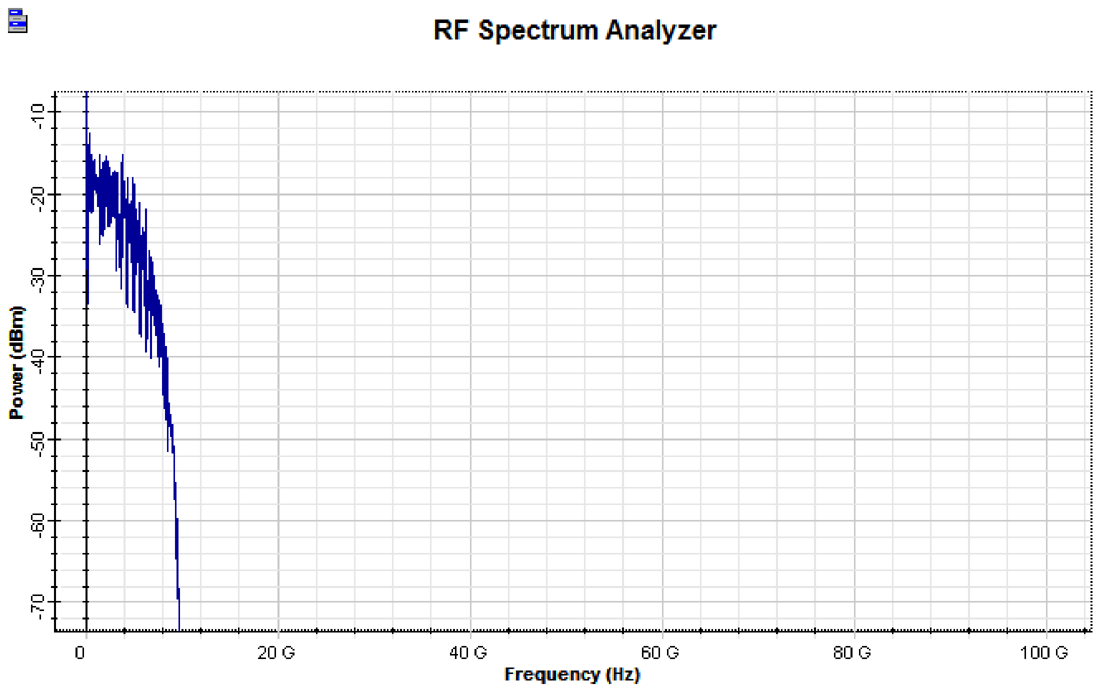


*Figure 4: Power spectrum of detected 10 Gbps using the raised cosine pulse generator.*

3.2.1 Create a subsystem that encapsulates the QAM Transmitter built in Figure 2. To idealize the transmitter, change the laser line width, MZM extinction ratio and the losses present in both the MZMs and the X couplers to values that will minimize distortion and noise. Idealize the receiver by modifying the local oscillator linewidth and by removing the noise from the photodetectors.

3.2.2 Replace the M-ary Pulse Generator components in the modulator with M-ary Raised Cosine Pulse Generators. Set the number of guard bits in the layout parameters to 16. Using the ideal transmitter find the spectral efficiency of 16 QAM, 64 QAM and 256 QAM formats. Plot the measured signal bandwidth at one of the Electrical Subtractor outputs.

3.2.1 Explain the significance of spectral efficiency and how it relates to a wavelength division multiplexed system.

# 4 REPORT

In your lab report include the following:

- Brief overview of the background and theory.
- Answers to all pre lab questions, clearly showing your work.
- Brief description of the simulation method and setup, including screenshots.
- Final results including figures and discussion.

# 5 REFERENCES


[1] Agrawal, G. P. *Fiber-optic Communication Systems*. New York: Wiley, 1997. Print