QAM Transmitter

1 OBJECTIVE

Investigate the method for measuring the BER accurately and the distortions present in coherent modulators.

2 PRE-LAB

The goal of optical communication systems is to transmit data from one point to another. Generally, this data takes the form of a binary signal. The binary data needs to be used to modulate an optical signal and then correctly demodulated at the receiver into a readable binary signal. Some simple schemes have already been described, like the pervasive on off keying, where the optical power is used to represent a '1' or '0'. However, power is only one aspect of the electric field and the phase can also be modulated. Describing the electric field with the complex envelope makes this clear:

$$E_t(t) = Re[E_x e^{i\phi_x - i\omega t}\hat{x} + E_y e^{i\phi_y - i\omega t}\hat{y}]. \tag{1}$$

From this equation, it is evident that for each polarization the amplitude can be changed and also the phase, ϕ_x. Amplitude modulation is a more general case of on-off keying (OOK) where the amplitude may take on more than two different levels. Modifying the phase, called phase shift keying (PSK), does not have an effect on the power of the output, but the phase of the optical carrier. Then there is the logical next step to modulate the amplitude and the phase at the same time called Quadrature Amplitude Modulation (QAM).

a)
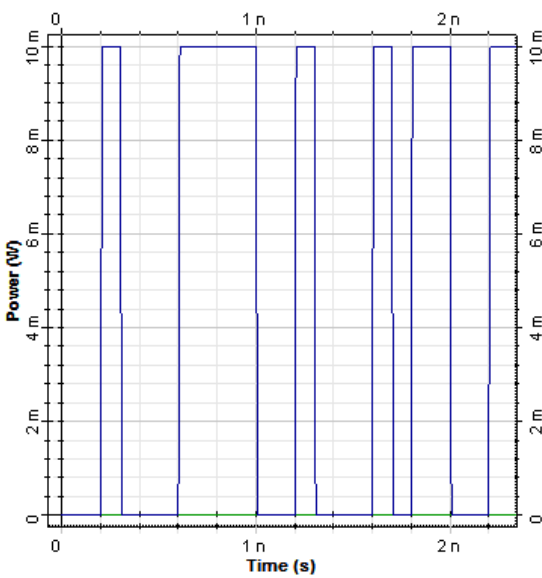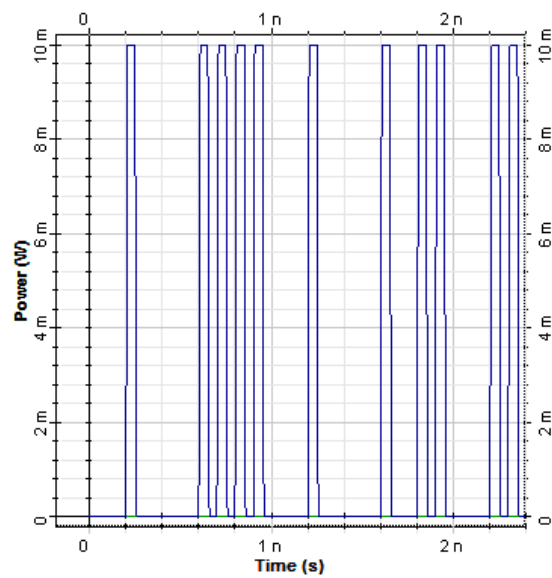
b)

Figure 1: An example of two different yet similar modulation formats. Figure a) represents an on off keying non return to zero format, while Figure b) shows a return to zero format.

2.1 BIT RATE, SYMBOL RATE AND BIT ERROR RATE

At this point the reader should be fairly confident to describe what the bit rate is. In any case, the bit rate is defined as the number of bits per second transmitted. The bit period, T_B, and in the special case of NRZ also the pulse width, would be given by:

$$T_B = \frac{1}{B}$$
(2)

In advanced modulation schemes instead of only having two states (on or off) there might be 4 or even 64 different states. The term bit is then replaced with symbol and bit rate replaced with symbol rate.

$$S = \frac{B}{log_2 M}$$
(3)

Here S is the symbol rate and M is the number of states that a symbol can take. For example, a system where the amplitude can be 0, 0.5, 1, 1.5 would have M = 4 and result in a symbol rate half that of a regular OOK format.

The bit error rate (BER) is an extremely useful metric for describing the quality of communication system. Simply put it is the number of misinterpreted bits per bit sequence transmitted.

$$BER = \frac{number\ of\ bit\ errors}{length\ of\ bit\ sequence}$$
(4)

The goal of communication systems is to keep this value low, while increasing the bit rate and at the same time keeping pecuniary costs low. This means that an accurate calculation of the BER depends on the length of the bit sequence. Suppose the true BER of a system is quite low, one error in a million bits or a BER of 10^{-6}, a simulation or laboratory test with only 1000 bits would only have a 0.1% chance of encountering a single bit error. Assuming that the experiment did result in an error, the BER would be incorrectly calculated as 10^{-3}, which is of course far off from the true BER.

The BER can also be estimated by inspecting the eye diagram from a NRS/RZ type format and for more advanced formats the constellation diagram can be used. In both of these cases though the longer the bit sequence the more accurate the results.

Build the following layout in OptiSystem to investigate the sequence length's effect on the BER.
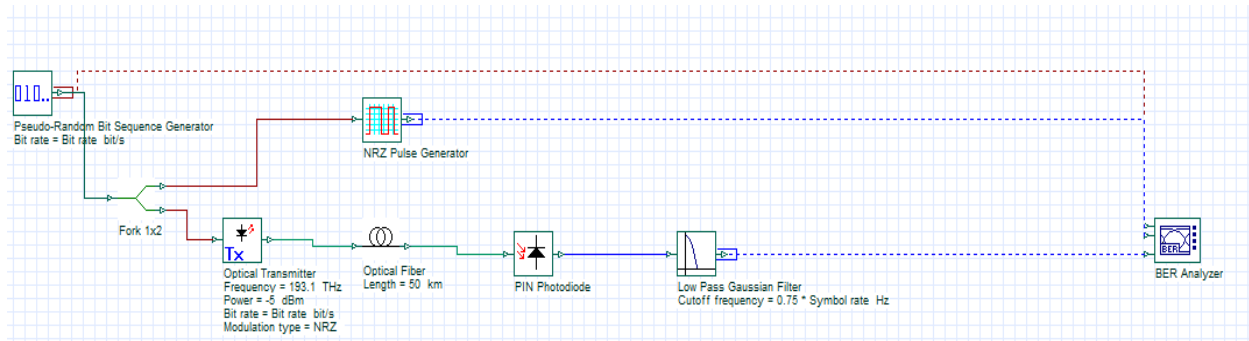
Figure 2: Layout for calculating BER of NRZ.

Once the components have been placed change the Power of the Optical Transmitter to -10 dBm and the Symbol rate, found in the layout parameters, to 10e+009 symbols/s

Questions:

2.1.1   Calculate the average BER and standard deviation from the Min. BER result given by the BER Analyzer for 25 identical simulations. The random noise and exact bit sequence will be the only changes.

2.1.2   Change the sequence length to 1024 and calculate the average BER and standard deviation from the Min. BER result given by the BER Analyzer for 25 identical simulations.

2.1.3   Change the sequence length to 4096 and calculate the average BER and standard deviation from the Min. BER result given by the BER Analyzer for 25 identical simulations. You may need to uncheck the BER Analyzer option "Eye must be open", since the eye becomes crowded from the numerous bits.

2.1.4   What is the effect of the sequence length on the calculated BER?

2.2   MODULATING LIGHT

Understanding the modulation scheme of OOK is quite simple, the receiver simply detects the power levels of signal and decodes it as a one or a zero. The important question is how to translate the electrical signal to an optical signal. In some simple systems, the pump current to the laser is modulated to change the intensity. This scheme is called direct modulation and normally results in pulses that are chirped from induced change in refractive index due to the change in carrier density. As chirped pulses are strongly affected by dispersion in optical fibers, directly modulated lasers are rarely used. A better method is to keep the laser at a steady current and modulate the signal externally with an alternate device.

A Mach Zehnder Modulator (MZM) can be used to modulate both the amplitude and phase of an optical signal. Without getting too detailed, the MZM splits the optical signal into two branches and induces a phase shift on each branch independently. At the output, the two signals are recombined and can result in a change in amplitude or phase. The response is given by:

$$E_{out} = \frac{E_{in}}{2}\left[e^{j\left(\frac{\pi V_1}{V_\pi}\right)} + e^{j\left(\frac{\pi V_2}{V_\pi}\right)}\right],\qquad(5)$$

where V_1 is the applied voltage at the top branch and V_2 is the applied voltage at the bottom branch. V_π is the required voltage to induce a PI phase shift to one of the arms. By varying the voltage on each arm, the amplitude can be modulated via constructive or destructive interference. By applying the same voltage to the top and bottom arms the phase can be changed as well.

<u>Questions:</u>

  2.2.1 What does the MZM response simplify to in the case where $V_2 = -V_1$?

  2.2.2 In the previous expression, consider the case where $V_1 = V(t) + V_{bias}$, what value of
      V_{bias} should be used such that the response is close to linear for small $V(t)$.
      Hint: $\sin x \approx x$ for $x \to 0$

2.3 QUADRATURE AMPLITUDE MODULATION

A special type of modulation which can easily be expanded to carrying many bits per symbol is quadrature amplitude modulation (QAM). At its core, it is the combination of modulating the phase as well as the amplitude and is expressed by the complex signal:

$$\boldsymbol{E}(t) = Re[(I(t) + iQ(t))e^{i\omega t}].\qquad(6)$$

One can take the view point that $Q(t)$ modulates the imaginary component of the complex envelope while $I(t)$ modulates the real part of the complex envelope. Removing the complex notation it becomes:

$$\boldsymbol{E}(t) = I(t)\cos \omega t - Q(t)\sin \omega t.\qquad(7)$$

The $Q(t)$ signal is out of phase by 90 degrees and gets the name quadrature phase carrier, while the other is the in-phase carrier. To visualize these different symbols, they are plotted on a complex plane or constellation. For example, a 4 QAM signal has two bits per symbol and $I(t)$ and $Q(t)$ can both take values of 1 and −1, representing a bit value 1 and 0. By removing the time domain from the equation, a constellation diagram can be used to view which symbols are present. For example, take Figure 1 below which is a representation of a 4 QAM signal. The binary sequence is cut into 2 bit length symbols where the first bit is translated for the $I(t)$ component and the second is translated for the $Q(t)$ component. To create the final signal, all that is needed is a way to modulate two sinusoids that differ in phase. To accomplish this, a CW laser can be split by a 3 dB cross coupler, which by its nature induces a π/2 phase shift.
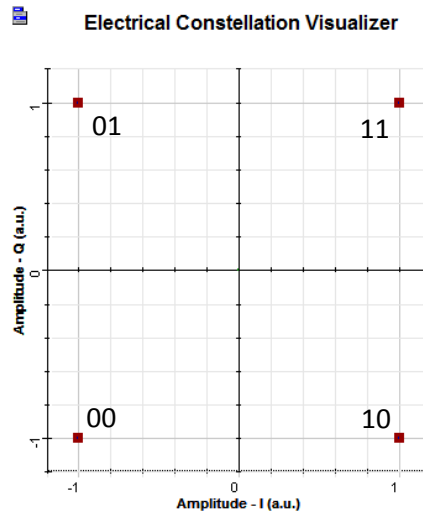
Figure 3: Constellation diagram of 4 QAM signal. Binary signals cut into 2 bit long symbols.

The following diagram demonstrates how a coherent transmitter could be designed. The binary sequence is split into and subsequently converted to the electrical signals, $I(t)$ and $Q(t)$. The electrical signals modulate their respective carriers, which differ by a $\pi/2$ phase shift due to the cross coupler.
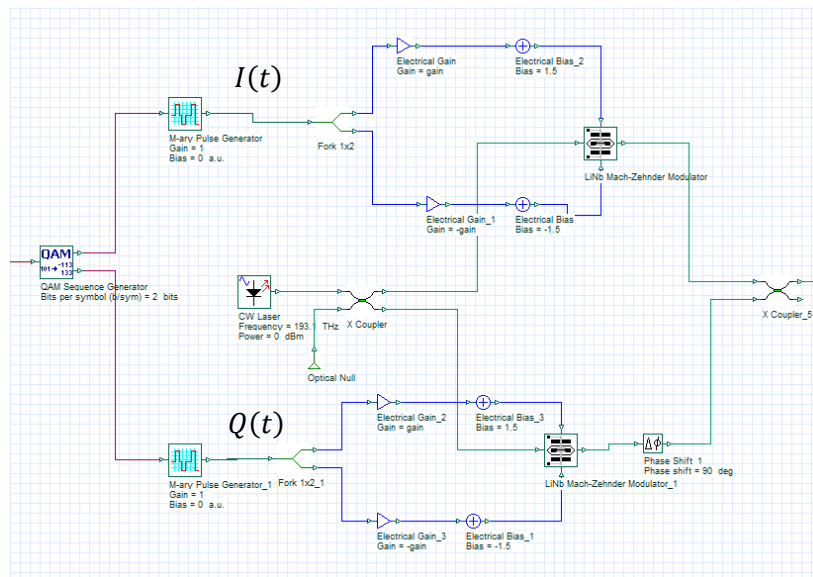

Figure 4: QAM transmitter design

2.3.1   The MZMs are held at the null bias point or a total bias voltage equal to V_π. This allows the time dependent portion of the signal to sweep through the maximum range of values before the periodic nature of the response duplicates values. What should the gain be if the M-ary Pulse Generator is outputting pulses of -1 and 1 Volts? What about a signal that ranges between -5V, -3V, -1V, 1V, 3V, 5V? Assume a V_π of 3 V.

2.3.2   In the constellation diagrams below convert the symbols in to bit sequences by the following protocol. First find the number of bits per symbol. The first half of the bits will

represent the $I(t)$ amplitude and the last half will represent the $Q(t)$ amplitude. Then, number the possible amplitudes starting from the smallest to the largest for each axis. Finally, locate the highlighted symbol and represent it as a binary sequence.

a)

b)

c)

d)
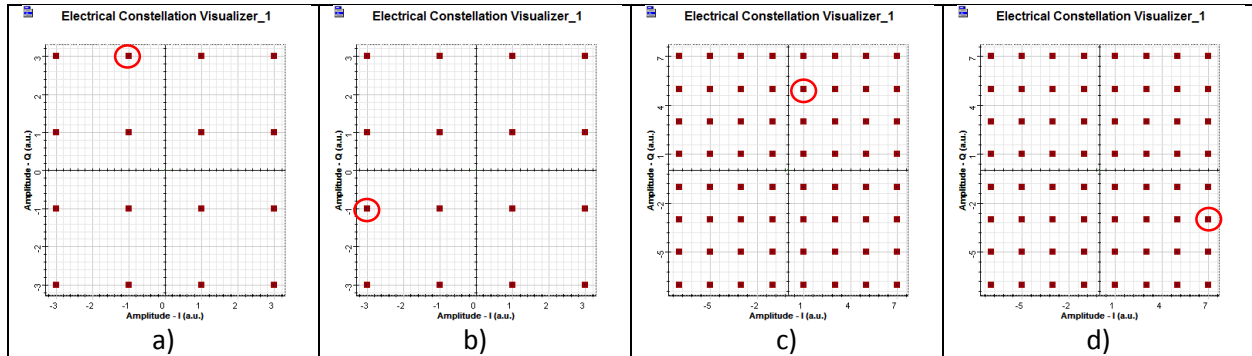
Example: In a) there are 16 possible states, which can be represented by 4 bits. The first two bits will represent the possible amplitudes for the in phase portion while the last two will represent the quadrature phase.

Bit Sequence	I(t)	Q(t)
0000	'00'–> −3	'00'–> −3
0001	'00'–> −3	'01'–> −1
0010	'00'–> −3	'10'–> 1
0011	'00'–> −3	'11'–> 3
0100	'01'–> −1	'00'–> −3
0101	'01'–> −1	'01'–> −1
0110	'01'–> −1	'10'–> 1
0111	**'01'–> −1**	**'11'–> 3**
1000	'10'–> 1	'00'–> −3
1001	'10'–> 1	'01'–> −1
1010	'10'–> 1	'10'–> 1
1011	'10'–> 1	'11'–> 3
1100	'11'–> 3	'00'–> −3
1101	'11'–> 3	'01'–> −1
1110	'11'–> 3	'10'–> 1
1111	'11'–> 3	'11'–> 3

In this labelling scheme the circled symbol results in the bit sequence '0111'.

3 DISTORTION IN QAM TRANSMITTERS

Build a QAM transmitter from the layout shown in Figure 3 and after creating a subsystem out of the components attach a bit sequence generator and a pre-built Optical Coherent QAM Receiver as in the diagram below:
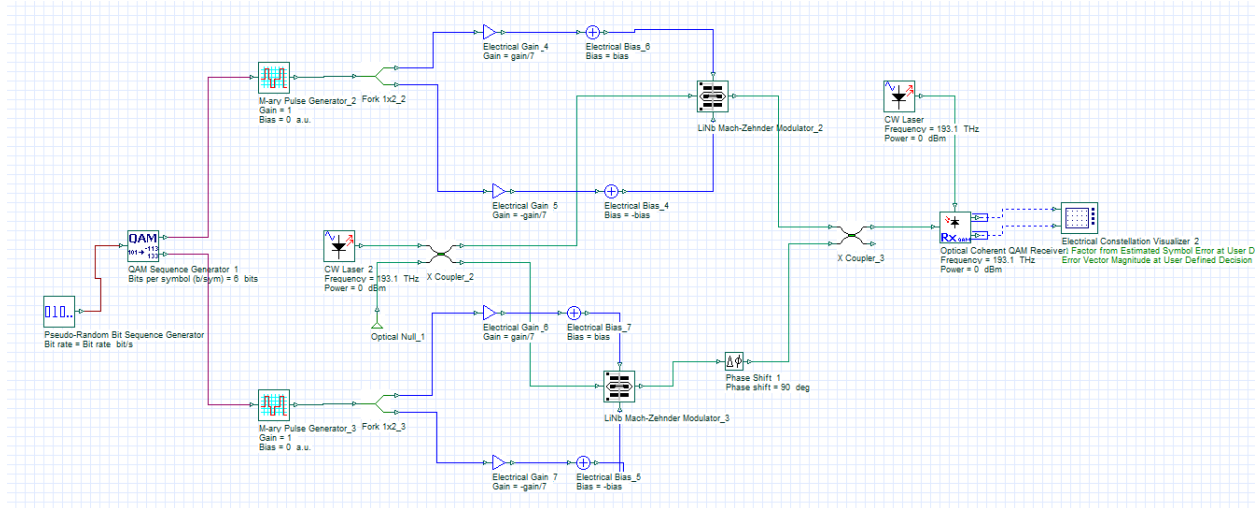

Figure 5: Layout of QAM transmitter.

- Pseudo-Random Bit Sequence Generator   Transmitters Library/Bit Sequence Generators
- QAM Sequence Generator   Transmitters Library/Coders
- M-ary Pulse Generator   Transmitters Library/Pulse Generators/Electrical
- Fork   Tools Library
- CW Laser   Transmitters Library/Optical Sources/
- Electrical Gain   Signal Processing/Arithmetic/Electrical
- Electrical Bias   Signal Processing/Arithmetic/Electrical
- LiNb Mach-Zehnder Modulator   Transmitters Library/Modulators/Optical
- Phase Shift   Passives Library/Optical
- X Coupler   Passives Library/Optical/Couplers
- Optical Coherent QAM Receiver   Receivers Library/Optical Receivers
- Electrical Constellation Visualizer   Visualizer Library/Electrical

The DC bias point for the two MZMs will be the null point or V_π and in this case that corresponds to a 1.5V bias at the top port and a -1.5V on the bottom port. In the LiNb MZMs make sure to change the Extinction Ratio to 25 dB, both switching voltages to 3V and the insertion loss to 1 dB. The X Couplers should also include a 1 dB insertion loss. The CW Lasers in this project are also slightly different as in coherent transmission links you need better phase characteristics of the transmitter. For the two CW Lasers change the Linewidth to 0.1 MHz and set them to operate at 193.1 THz. The optical coherent receiver can be set to accept an external local oscillator (laser), a necessary additional component in coherent receivers that will be explained in a later laboratory. At this stage the assumption that both

lasers have the exact same phase characteristics will be made to simplify the design. In the Component Properties of the two CW Lasers change the Random seed index to 0 for both.

3.1   EFFECT OF GAIN

The constructed QAM Optical Transmitter can be modified easily to obtain both 4 QAM and 64 QAM, first set the transmitter to function as a 4 QAM transmitter by setting the Bits per symbol appropriately.

Questions:

3.1.1   Assuming the default bit rate of 10 Gbps, what should the Layout Parameter Symbol rate be set to for 4 QAM and 64 QAM?

3.1.2   What is the maximum gain that should be used for the case of 4 QAM and 64 QAM?

3.1.3   Simulate the effect of the gain on the 4 QAM constellation at the output starting from the maximum gain value and ending at 0.1. Compare the first and final constellations and describe what the effect of the gain on the constellation. There will be some random noise generated by the photodetectors in the optical receiver.

3.1.4   The off center characteristic of the constellation is due to an additional term in the transfer function of the MZMs, that was not explained in the pre-lab but has an important effect nevertheless. Find the transfer function in the technical background and explain which parameter is responsible for this behavior.

3.1.5   Simulate the effect of the gain on the 64 QAM constellation at the output starting from the maximum gain value and ending at 0.1. Compare the first and final constellations and describe what the effect of the gain on the constellation.

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