II. Review of Modulation Formats

This Appendix reviews the most important modulation formats relevant for this thesis. For additional background, [1] provides an excellent tutorial which details the advantages and disadvantages of these and many other popular modulation formats.

A.2.1 Mach-Zehnder Modulator

This thesis is concerned with modulation formats created using zero-chirp MZMs. While the modulation of light is possible through other means (e.g. electro-absorption modulators, directly modulated lasers, etc…), the MZM remains the proven technology for high speed optical systems.

The MZM manipulates light through the electro-optic (EO) effect. When an electrical voltage is applied across an EO material such as $LiNbO_3$, the effective refractive index of the waveguide changes. By applying a differential phase delay between two parallel paths, light intensity is modulated after recombining owing to constructive and destructive interference [2]. The output electric field of the MZM is

$$E_{out}(t) = E_{in}(t)\cos\left(\frac{\pi}{2}\left(V_d(t) + \frac{V_{bias}}{2}\right)\right)\exp\left[i\,\frac{\pi V_{bias}}{4}\right] \qquad \text{(A.2.1)}$$

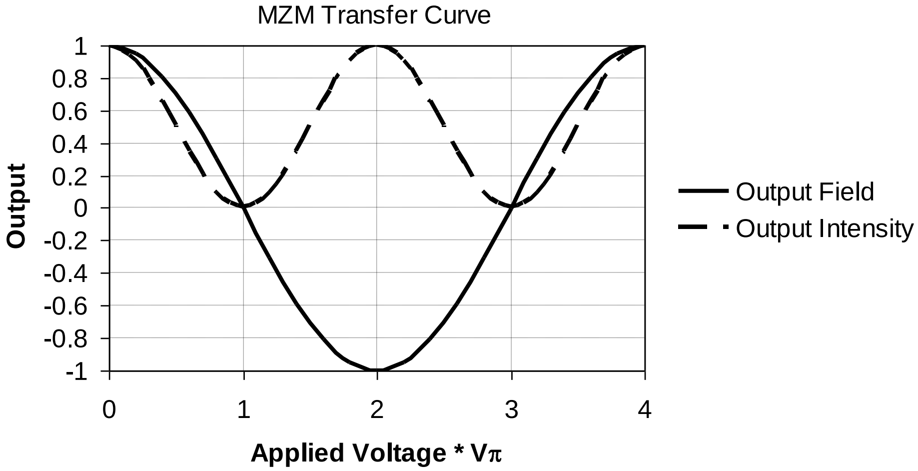

Fig. A.2.1. Transfer characteristic of a typical MZM. The solid line corresponds to the field and the dashed line corresponds to the intensity (i.e. the magnitude-squared of the field).

where $E_{in}(t)$ is the input field, $V_d(t)$ is the electrical driving voltage waveform and V_{bias} is the DC bias applied to the MZM arms. The transfer curve of (A.2.1) is shown in Fig. A.2.1 for an offset bias,V_{bias}, of 0 V. It is evident that by modulating between, for example, 0 and V_π that the light wave can be modulated between 1 and 0 intensity. Moreover, it can be seen that an additional π phase shift occurs when the voltage swings, for example, between 0 and $2V_\pi$ since the field amplitude changes between 1 and -1. This phase flipping property is commonly used both for creating phase modulated signals and phase coded intensity modulated formats [1, 3].

A.2.2 Non-return to Zero Modulation

The most straightforward intensity modulated format is NRZ. NRZ is created by modulated between 0 and V_π on the MZM transfer curve and is characterized by the fact that consecutive marks do not return to zero between bits. Thus, long strings

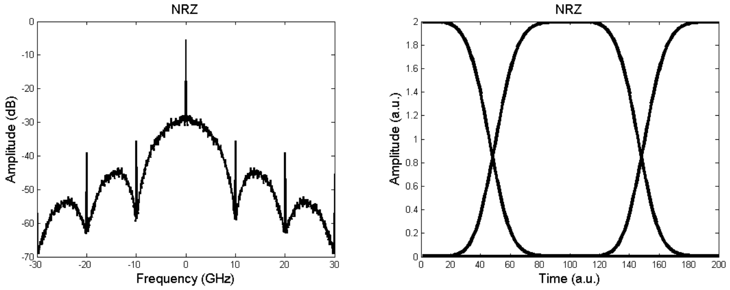

Fig. A.2.2. NRZ PSD and eye diagrams at 10 Gb/s.

of marks tend to have large amounts of low frequency information. Additionally, since the driving voltage only swings by V_π, no phase flipping occurs in the transmitted field. Optical NRZ modulation is considered a unipolar form of NRZ signaling and therefore has a strong DC component which exceeds 50% of the total energy for finite ER signals (assuming equal probability marks and spaces). The characteristic sinc-like PSD and the corresponding eye diagram for NRZ are shown in Fig. A.2.2.

A.2.3 Return to Zero Modulation

In contrast to NRZ, all RZ modulation formats are characterized by the fact that adjacent marks are separated by periods in which the magnitude returns to the low level. Optical RZ formats are categorized by their duty cycle and phase coding. Three of the most typical RZ formats are 50% RZ (RZ50), 33% RZ (RZ33) and carrier suppressed RZ (CSRZ).

A typical RZ transmitter consists of two serially connected MZMs as shown in Fig. A.2.3. The first MZM is modulated by the standard NRZ data sequence to imprint the information onto the lightwave. The second MZM is driven by a sinusoidal

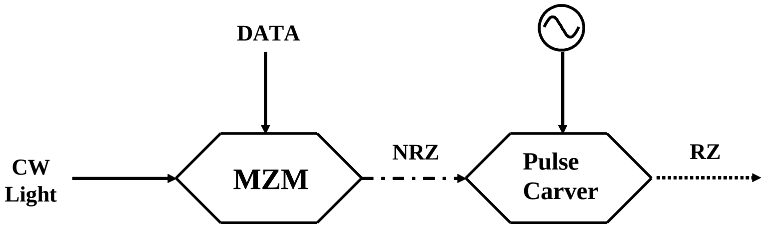

Fig. A.2.3. Typical RZ transmitter using two cascaded MZMs. The first MZM imparts the data using standard NRZ modulation. The second MZM careves the RZ pulses.

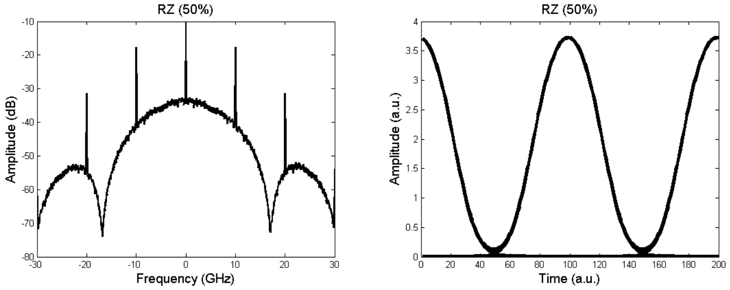

Fig. A.2.4. NRZ PSD and eye diagrams at 10 Gb/s.

electrical signal and is used as a pulse carver thus ensuring that consecutive marks are separated by dips back zero. The benefits of RZ are many: clock recovery of the transmitted data is easier, ISI effects are less pronounced, higher sensitivities can be achieved and penalties from coherent RB are lower [1, 4]. However, RZ formats also have drawbacks owing to their significantly wider spectra. This implies that RZ formats are spectrally wasteful and inherently inferior for achieving a high spectral efficiency. A further consequence is that RZ formats will suffer from greater amounts of optical filtering penalties since *filter concatenation* effects will be more severe [5].

The creation of the various RZ varieties depends on the nature of the pulse carver driving signal. In order to create RZ50, the pulse carve is driven with a V_π voltage (peak to peak) swing sinusoid at the data rate, R, which is biased in quadrature

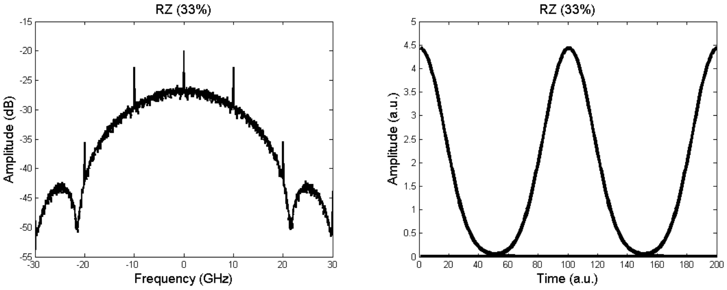

Fig. A.2.5. RZ33 PSD and eye diagrams at 10 Gb/s.

(i.e. at $V_\pi/2$ in Fig. A.2.1). The resultant pulses have an approximate 50% duty cycle and no additional phase flipping. The corresponding PSD and eye diagram is shown in Fig. A.2.4.

RZ33 is created by driving the pulse carver with a $2V_\pi$ voltage (peak to peak) swing sinusoid at half the data rate, R/2, which is biased at the maximum of the transfer curve. The carved pulsed have a duty cycle of approximately 33% the bit period. This narrower effective pulse translates to a correspondingly larger amount of high frequency energy as shown in Fig. A.2.5. Again, no phase flipping occurs for RZ33.

CSRZ is created by driving the pulse carver with a $2V_\pi$ voltage (peak to peak) swing sinusoid at half the data rate, R/2, which is biased at the null of the transfer curve. The key effect of this type of pulse carving is that the duty cycle is about 67% and adjacent pulses always have alternating zero and π phase. In other words, the DC tone averages to zero since alternating bits have opposite phase. Hence, the carrier is suppressed on average and, instead, harmonic tones at +/- R/2 appear as shown in Fig. A.2.6. Conveniently, this phase flipping does not affect receiver design since the all

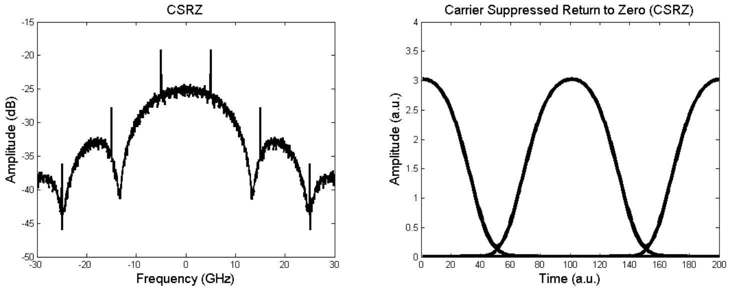

Fig. A.2.6. CSRZ PSD and eye diagrams at 10 Gb/s.

phase information is lost during the process of square-law detection. To the receiver, there is no difference between a +1 pulse and a -1 pulse. The motivation to incorporate phase flipping in the transmitted signal is prompted by other influences such as propagation nonlinearities and filtering effects.

A.2.4 Duobinary

Another class of intensity modulated signals known as partial response signals. These signals are similar to CSRZ in the sense that some bits are flipped by π phase with respect to others. However, partial response coding implies that these phase flips are positioned according to the transmitted bit pattern. Hence, partial response signals require an additional coding layer and different drive electronics than CSRZ.

A particularly important partial response code in optical communications is DB [6-8]. DB has many interesting properties which makes it advantageous in certain situations. Particularly, DB is spectrally compressed compared to NRZ, carrier suppressed (because of the intrinsic phase coding) and highly resistant to ISI [9-12]. These features make DB an ideal candidate for high spectral efficiency systems and metropolitan area networks.

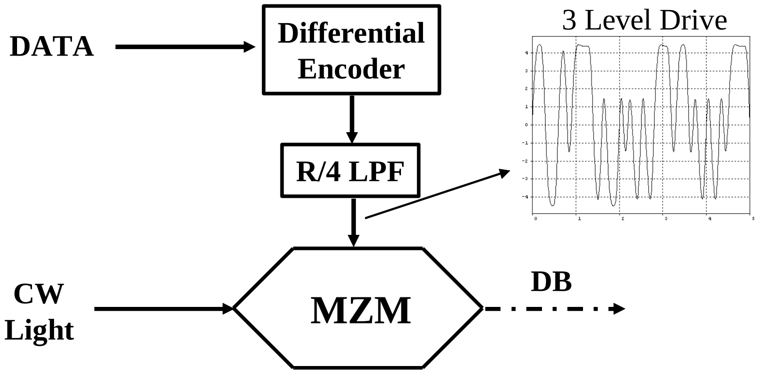

Fig. A.2.7. Typical LPF DB transmitter. The 2 level binary data is converted to a 3 level waveform via heavy lowpass filtering. The inset shows an example of the 3 level waveform used to drive the MZM.

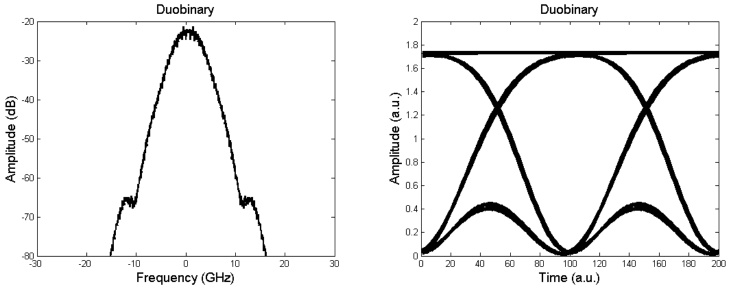

Fig. A.2.8. DB PSD and eye diagrams at 10 Gb/s.

To attain these benefits however, the DB transmitter requires additional equipment and is known to be more sensitive to tolerancing error [13]. The schematic of the most common DB transmitter is shown in Fig. A.2.7. The raw data signal is first passed through a differential encoder. The differential encoder consists of an XOR gate and a 1-bit delay. The output of this logic step creates correlations between bits. The encoded sequence then passes through a LPF which has an approximate cutoff around R/4. Typical LPF used for optical DB are 5th order Bessel filters. The heavy filtering causes the original, 2 level digital signal to convert to a 3 level signal as exemplified in the inset of Fig. A.2.7. The 3 level filtered waveform is biased at the

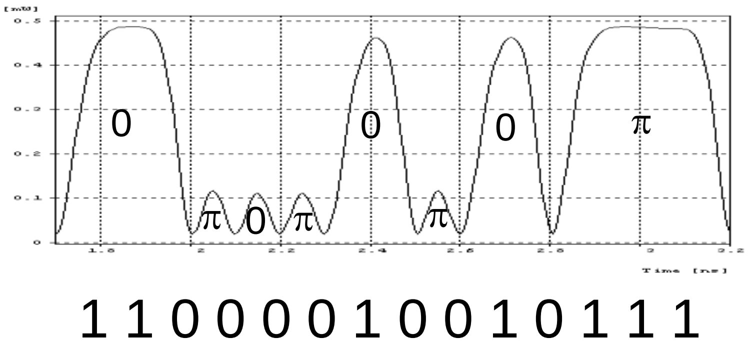

Fig. A.2.9. Typical DB intensity waveform making use of phase flips in the middle of each space period. The zero-ripple has a duplicitous effect: it causes an excess power penalty while simultaneously improving the ISI immunity.

null of the MZM transfer curve and modulated the CW light between the 0, V_π and $2V_\pi$ points. The modulated light has a PSD and eye diagram illustrated in Fig. A.2.8.

The DB signal will follow a phase flipping algorithm which dictates that a π phase flip will occur during the middle of ever space period. Marks separated by an odd number spaces will be 180^o out of phase with each other as shown in Fig. A.2.9. This feature gives DB a higher immunity to CD and optical filtering effects because overlapping energy from marks separated by a single space (i.e. a 1 0 1 bit pattern) tends to destructively cancel, thereby preserving the low space level [6,14].

A.2.5 References

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