RZ vs. NRZ

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In telecommunication systems, there are several different digital data waveforms in use. They include variations on neutral, unipolar, polar, NRZ, RZ, and bi-phase. There are also several different modulation schemes in use, including Amplitude (ASK), Frequency (FSK), and Phase (PSK). For fiber optic telecommunications, by far the most commonly used data waveform is NRZ in conjunction with amplitude on/off modulation. Most data transmission over fiber optics at 10 Gb/s and lower data rates has been using the NRZ format. There are a few long haul, proprietary systems that use the RZ format and up to 25% Forward Error Correction (FEC) at bit rates up to 12.5 Gb/s. Researchers have found huge problems associated with fiber dispersion over long distances when using the NRZ format at 40 Gb/s. They have found that by using "Solitons" in the RZ format they can achieve significant improvements. Here at PSPL, we are seeing increasing interest from our customers for using the RZ format with our products. The purpose of this application note is to discuss the differences between the RZ and NRZ formats and the implications for amplifier capabilities, bandwidth requirements, and instrumentation.

Non-Return-to-Zero
The most common form for a digital logic signal is the Non-Return-to-Zero, or NRZ for short. This is the type of logic all engineers and techs were first introduced to in school in the first logic lab using TTL ICs. Figure 1 shows a typical NRZ data stream. A logic "one" is defined as the high voltage state, while a logic "zero" is defined as the low voltage state. Oftentimes, there is also a logic clock signal associated with a logic circuit. The bottom trace in Figure 1 is the clock. If at each "tick" of the clock, the logic signal (Figure 1, top trace) switches to the opposite state, then a pulse transition edge occurs. If, however, there is no logic state change, then no pulse transition edge occurs, i.e., there is a "non-return-to-zero". If a string of "ones" is transmitted, there are no transitions. Likewise, if a string of "zeros" is transmitted, there are no transitions. In these situations with no transitions, an NRZ signal appears to have a "DC" nature.

Return-to-Zero
Figure 2's top trace shows a data stream of Return-to-Zero or RZ signals. The lower trace is the associated logic clock signal. The definition of RZ logic is if the logic state is a "one", then a pulse of 1/2 the clock period occurs. If the logic state is a "zero", then no pulse occurs, and the signal remains at the baseline. Obviously, due to its basic pulse nature, an RZ signal has many more transitions compared to NRZ, and less "DC" content.

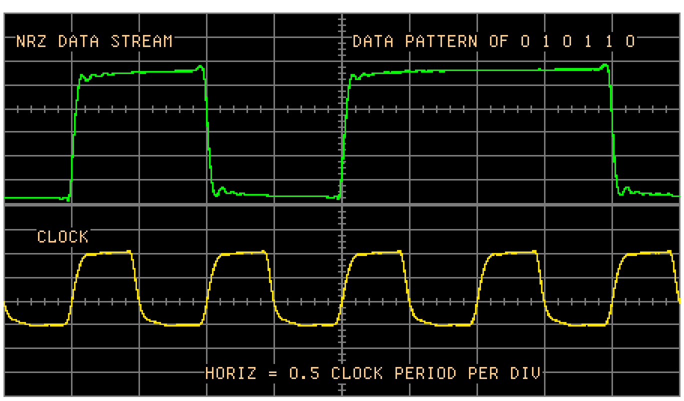


Figure 1: An NRZ data stream plus clock

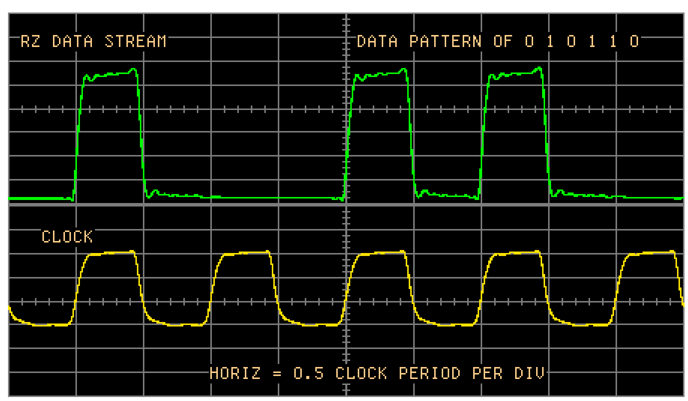


Figure 2: An RZ data stream plus clock

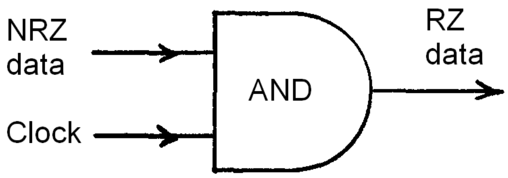


Figure 3: NRZ to RZ conversion

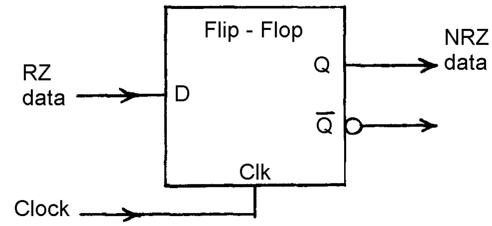


Figure 4: RZ to NRZ conversion

Conversion between NRZ and RZ
Most data systems will use NRZ at lower bit rates. Thus there typically will be some portion of an RZ transmission system that converts NRZ to RZ and vice versa. This RZ conversion typically occurs at the highest data rate in the system. Figure 3 shows the typical manner in which NRZ is converted to RZ. A dual input AND gate is used. One input is the incoming NRZ data stream. The other is the Clock signal. This might be done using a very high-speed logic IC. In a fiber system, the AND function could also be accomplished using two cascaded electro/optical modulators. The first E/O modulator would have a CW laser optical input and an electrical input of a sine wave at the clock frequency. The output would then be an optical pulse train at the clock frequency. This would then be the optical input into the second E/O modulator. The electrical input to this second modulator would be the NRZ data stream. The E/O output would thus become an RZ optical data stream.

To demodulate an RZ data stream into an NRZ data stream requires a "D" type flip-flop. See Figure 4. The RZ signal is applied to the "D" or "Data" input. The recovered clock is applied to the "Clk" input. The timing of the clock must be delayed and precisely positioned to be centered on the RZ data pulse. The output of the flip-flop is now an NRZ data stream.

Eye Diagrams
The most fundamental instrument used for time domain measurements is the oscilloscope. However, it is difficult to design, characterize, or trouble-shoot a digital system by simply looking at really long strings of data, such as Figures 1 and 2. For data systems, the most commonly used oscilloscope measurement is instead an "Eye" diagram. Figure 5 is an example. For an eye diagram, the horizontal sweep is set for a time window of two clock periods. The oscilloscope is then triggered by the system clock. In the eye diagram mode, the oscilloscope is operated much like a multiple exposure camera. The display is set for infinite persistence. Each time the oscilloscope is triggered, a rapid sweep occurs, and whatever data signal was present gets permanently recorded on the display. As time goes on, almost every possible combination of data events will be measured and superimposed upon the display. Modern digital sampling oscilloscopes include the capability to fill their pixel display memories with the information of the number of occurrences at each pixel. They then use various colors to convey the statistical nature of the occurrences. This is called a "color-graded display".

Figures 5 and 6 are of nearly ideal eye diagrams for NRZ and RZ, respectively. The ideal eye diagram will look box-shaped, with nearly vertical transitions. The center of the box (or eye) will be wide open and free from any signals. When this center region starts to be filled with slowly rising and falling data transitions, vertical noise, timing jitter, and other waveform imperfections, the eye is said to be closing. When the eye closes, the bit error rate dramatically increases. For all of the eye diagram examples in this application note, a Pseudo Random Binary Sequence (PRBS) of 2^{6} bits was used.

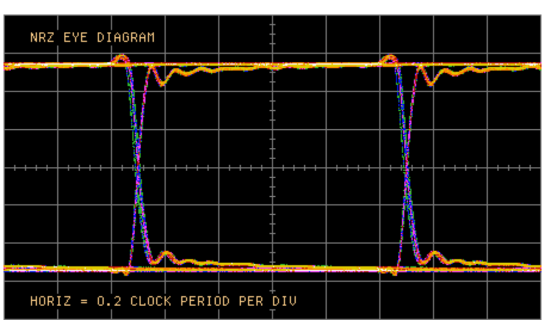


Figure 5: Nearly ideal eye diagram of NRZ data

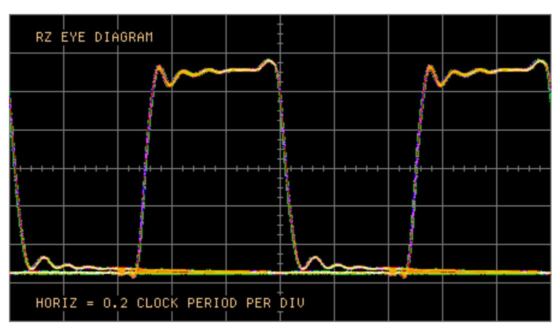


Figure 6: Nearly ideal eye diagram of RZ data

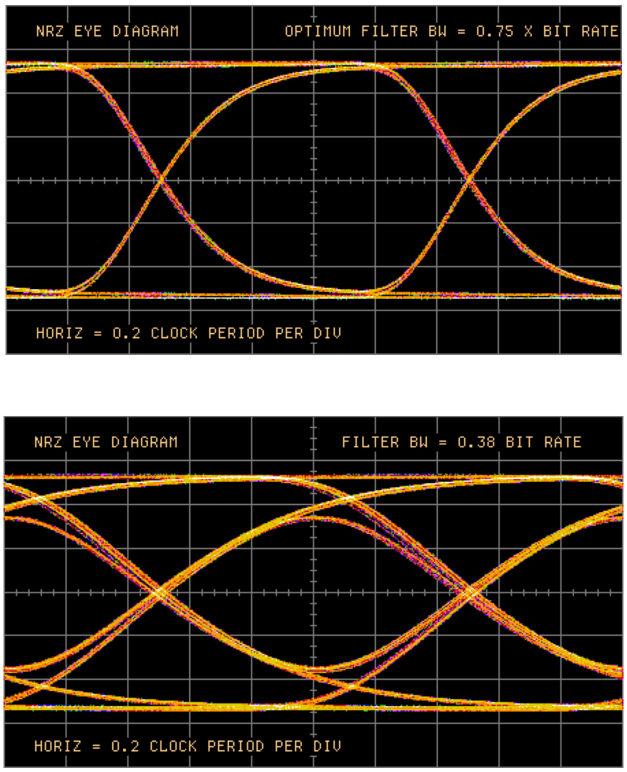


Figure 7: Limited bandwidth NRZ eye diagrams

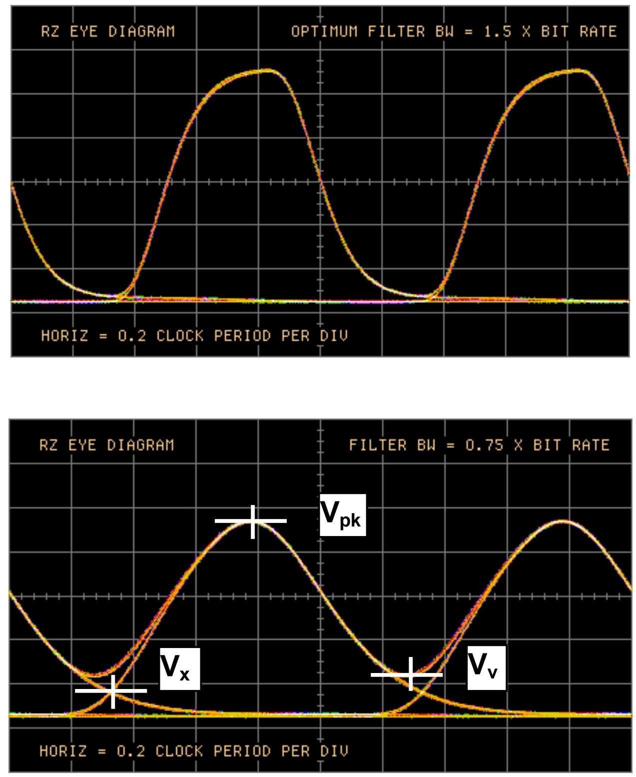
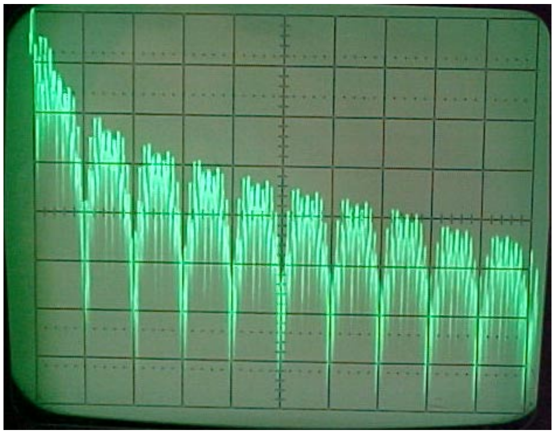


Figure 8: Limited bandwidth RZ eye diagrams

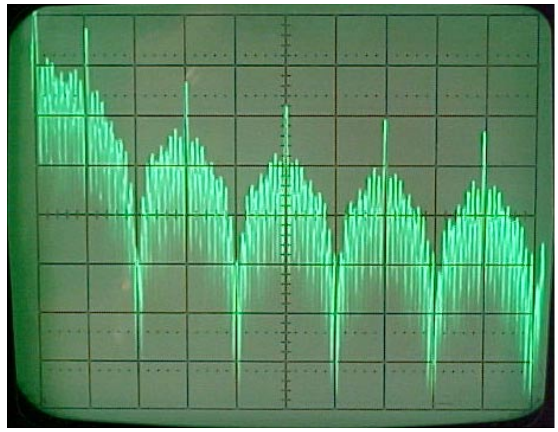
Filtered Eyes

Most practical data systems do not in fact operate with ideal box-shaped eyes such as those shown in Figures 5 and 6. One typically tries to maximize the data rate going through a limited bandwidth system. A limited bandwidth has the effect of slowing down fast edge, pulse transitions. A standard equation relating band-width and risetime (or falltime) is: $BW * T_r = 0.35$, where BW is the -3dB bandwidth of the system, and T_r is the 10%-90% step response risetime. **Note:** This equation is only truly valid for a near Gaussian-like system. For example, the risetime of a 10 GHz bandwidth system would be 35 ps. Figure 7 shows the effect on NRZ eye diagrams of limiting the bandwidth to 3/4 and 3/8ths of the bit rate.Figure 8 shows the effect on RZ eye diagrams of limiting the bandwidth to 1.5 and 3/4ths of the bit rate.

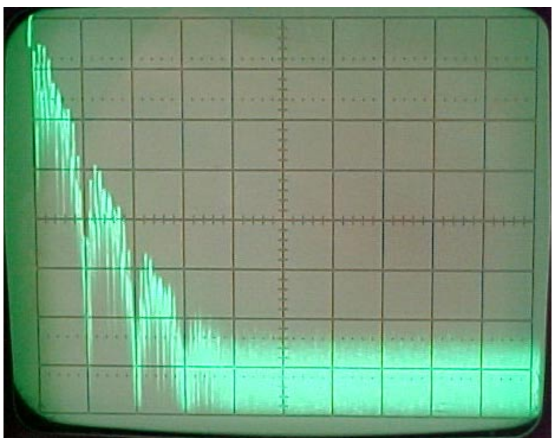
Low pass filters used to control the bandwidth of data systems must have a Gaussian-like response. A Gaussian filter's only effect is to slow down rise/ falltimes. Any other type filter will introduce additional severe waveform distortions, including over/under-shoots and ringing. PSPL's various low pass filters are ideal for this application. For additional reading on low pass filters, please refer to PSPL's application note, AN-7a.



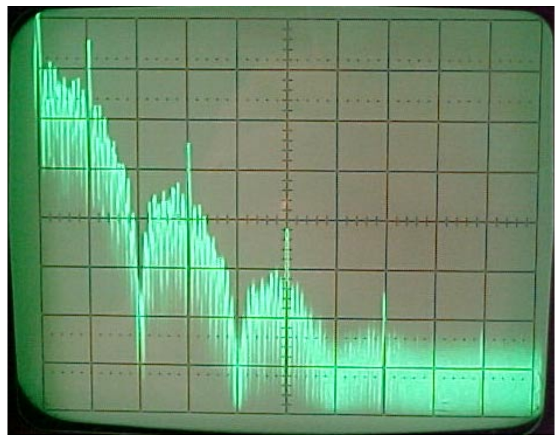
NRZ data (see Figure 1)



RZ data (see Figure 2)



Filtered NRZ data, BW = 0.75 * Bit Rate



Filtered RZ data, BW = 1.5 * Bit Rate

Figure 9: Spectrums of various NRZ and RZ data streams. Vert = 10 dB/div. Horiz = 1 Bit Rate unit/div.

NRZ and RZ Spectrums

It is also informative to study the spectral content of both NRZ and RZ data. Figure 9 shows the respective spectrums for both the unfiltered and filtered data streams. RZ data has higher spectral content compared to NRZ. Another observation is that a very strong clock spectral line exists in the RZ spectrum, whereas a spectral null occurs at the clock frequency for NRZ data. This makes clock recovery simpler when using RZ data.

Bandwidth Requirements

The major conclusion for comparing RZ vs. NRZ is that an RZ data signal requires twice the bandwidth of an NRZ data signal operating at the same bit rate. The bandwidth of an NRZ channel can be lowered down to as low as 0.75 * Bit Rate before any degradation of the eye height or eye width occurs. Any further bandwidth filtering starts to rapidly degrade the eye. The bandwidth of an RZ channel can be lowered only down to as low as 1.5 * Bit Rate before eye diagram degradation occurs. For RZ bandwidths less than 1.5 * Bit Rate, the eye amplitude, V_{pk}, rapidly drops, and the valley point, V_v, and cross point, V_x, rapidly grow. The valley points are due to incomplete extinction of pulses for a continuous sequence of "one" pulses. The cross points are due to alternating sequences of "ones" and "zeros". See Figure 8, lower plot, for an example.

This also has implications on the requirements for measurement instruments. To accurately measure 40 Gb/s RZ electrical signals mandates that the measurement oscilloscope must have a -3dB bandwidth of at least 60 GHz and risetime of less than 5.8 ps. For optical 40 Gb/s RZ signals, the combined bandwidth of both the oscilloscope and photodiode must be in excess of 60 GHz.

Low Cost RZ to NRZ Converter

At the highest data rates of 10Gb/s to 40 Gb/s, D flip-flops such as shown in Figure 4 are either very expensive or non-existent. A simple approach to converting an RZ signal into an NRZ signal is to over-filter the RZ signal. Figure 10 shows the resultant eye diagram of filtering an RZ signal with a Gaussian filter with a -3dB bandwidth of 3/8ths the Bit Rate. The results are not perfect, but in some situations could be useable. PSPL has developed a proprietary RZ to NRZ converter filter that produces perfect conversion. Its disadvantages are -6 dB insertion loss and poor return loss, and it will only operate for a specific bit rate.

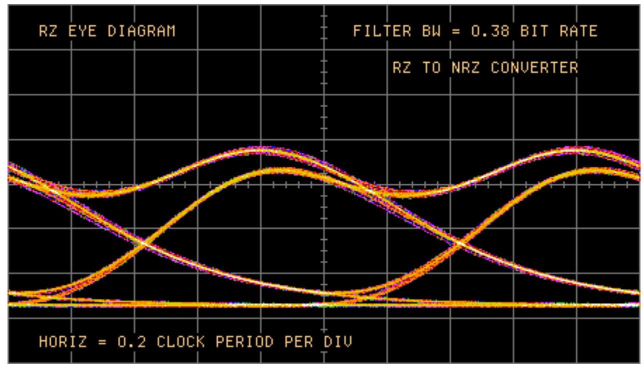


Figure 10: RZ to NRZ Filter

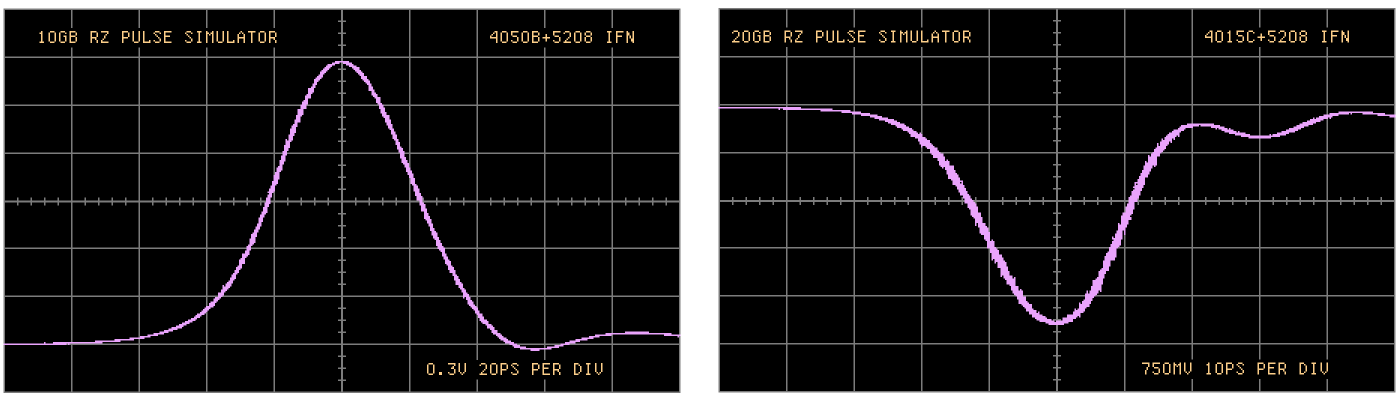


Figure 11: Simulated 10 Gb/s RZ impulses from PSPL 4050B and 4015C pulse generators

10 and 20 Gb/s RZ Pulse Generators

At present, no test instrument manufacturer offers for sale RZ data generators operating at clock rates of 10 Gb/s or higher. All of the 10 to 40 Gb/s data generators on the market are extremely expensive and only produce NRZ outputs. Researchers needing RZ signals are forced to create their own RZ signals. PSPL offers some much lower cost picosecond pulse generators that can be used to simulate 10 and 20 Gb/s RZ signals for R&D purposes. The PSPL model 4050B pulse generator produces a +10 V, 45 ps risetime, 10 ns step pulse. (Note: The PSPL model 10,050A is a programmable version of the 4050B.) The PSPL model 4015C pulse generator produces a -9 V, 15 ps falltime, 5 ns step pulse. With a PSPL model 5208 Impulse Forming Network attached to the output of the 4050B, the 1.75 V, 46 ps impulse shown in Figure 11 is produced. Using the 5208 on the 4015C, a -3.4 V, 22 ps impulse is produced.

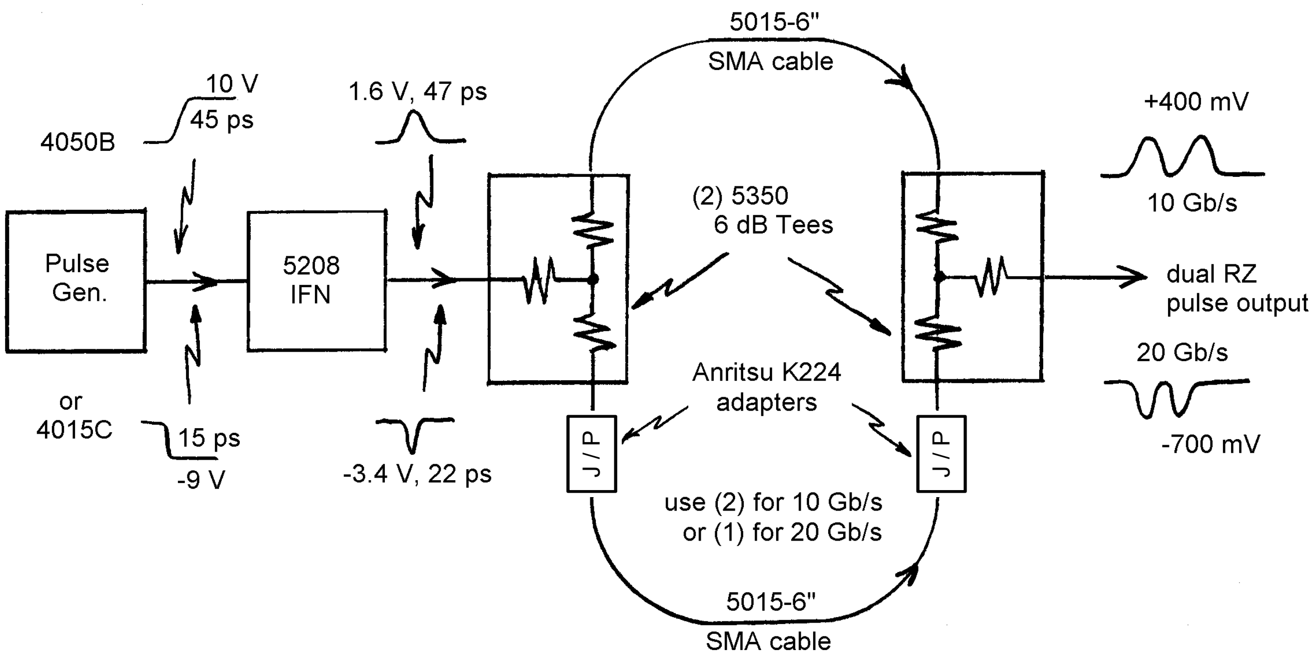
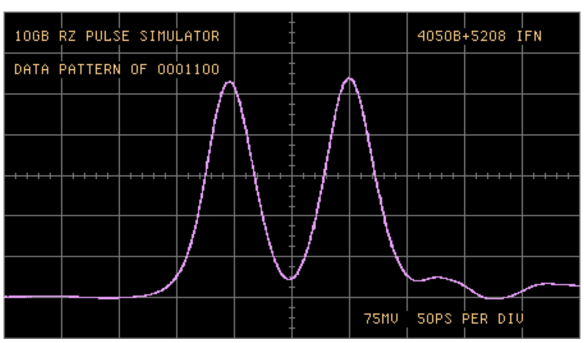


Figure 12: RZ Dual Pulse Simulator



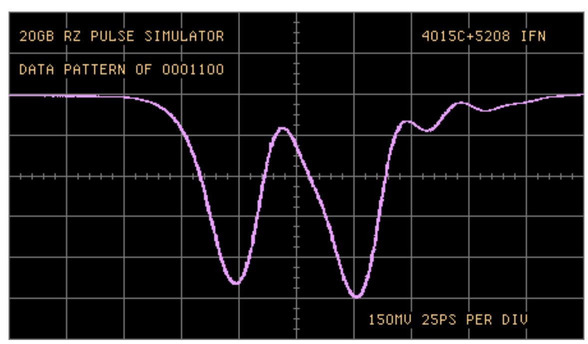


Figure 13: Simulated 10 and 20 Gb/s RZ pattern sequences of 0 0 0 1 1 0 0, using PSPL impulse generators

These impulses can be used to simulate either a single 10 Gb/s or 20 Gb/s RZ pulse, respectively. The major limitation of these generators is their rep. rate. They are not capable of actually operating at Gb/s rates. Their max. rep. rates are 1 MHz and 500 kHz, respectively. One can also simulate a pair of 10 or 20 Gb/s RZ pulses using these generators. Figure 12 shows an arrangement of PSPL passive components to accomplish this.

A pair of PSPL model 5350, dc-40 GHz, 6 dB power divider tees are used to first split and then recombine a single impulse into a pair of impulses. Two coaxial cables of unequal length are used to provide the offset delay between the two impulses. The resultant, simulated 10 and 20 Gb/s RZ signals are shown in Figure 13. The 10 Gb/s dual RZ pulse amplitude is 400 mV. The 20 Gb/s dual RZ amplitude is -700 mV.

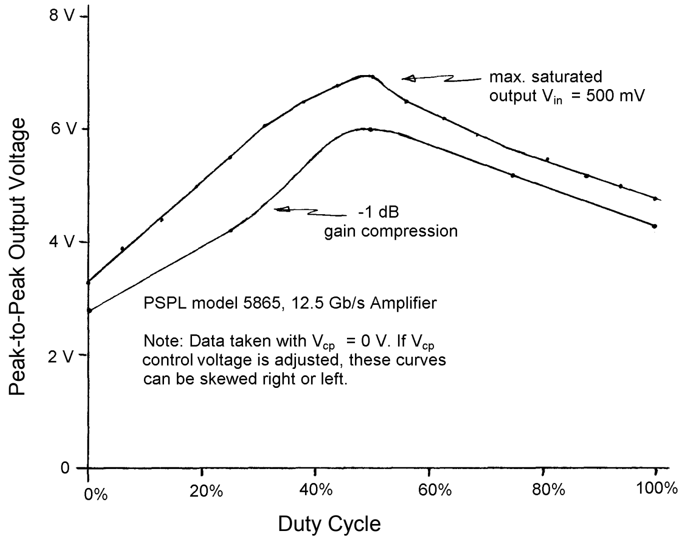


Figure 14: Amplifier max. output amplitude vs. input signal duty cycle

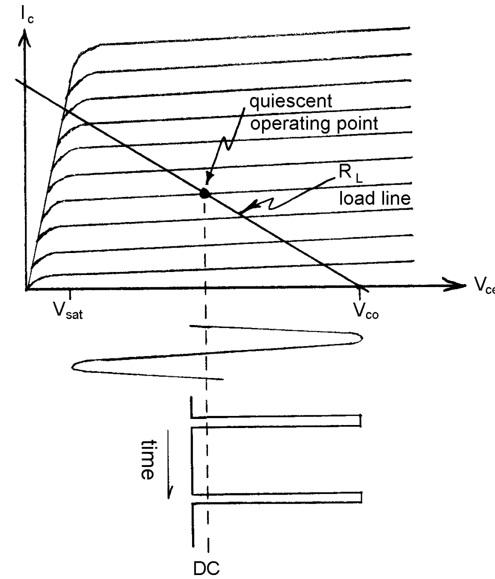


Figure 15: A Typical class A amplifier load line analysis

RZ vs. NRZ Amplifiers

A general statement can be made that the max. output amplitude from an amplifier amplifying RZ signals will be less than with NRZ signals. The max. output amplitude from an amplifier is strongly dependent upon the duty cycle of the input signal, Figure 14. This can be explained from a load line analysis of a typical transistor amplifier, Figure 15. For a class A amplifier, the operating quiescent bias point is typically situated near the middle of the load line. This allows nearly equal output voltage swings either towards saturation or cut-off. The max. peak-to-peak output for a sine wave or square wave reaches both the saturation point and the cut-off point. $V_{ptp} = V_{co} - V_{sat}$. If, however, a narrow, isolated, single pulse is input to the amplifier, its effective dc value is near zero. Depending upon its polarity, this single pulse either swings from the amplifier's quiescent bias point to either saturation or cut-off, but not to both. If the operating point is in the center, then we would expect the max. output amplitude for a pulse with a duty cycle of < 1% to be about 1/2 of a 50% duty cycle signal. When dealing with purely random data, the duty cycle of NRZ data is 50% and 25% for RZ data. Thus, the ratio of RZ / NRZ max. output amplitudes will typically be about 75%. If an amplifier is specifically designed for RZ service, then its quiescent operating point can be shifted off of center to maximize its unipolar swing. The example shown here is for the PSPL model 5865 amplifier. It produces 7 V_{ptp} output with NRZ data, but only 5.6 V_{ptp} for RZ data. The 5865, however, includes a "crossing point" adjustment pin. A dc control voltage on this pin allows the amplifier's operating point to be adjusted by the user. When this adjustment is made, RZ amplitudes up to +7 V or -6 V can be obtained.