3480 RECORDING-CHANNEL DEVELOPMENT

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ABSTRACT

The 3480 recording-channel electronics represents several advances in the state of the art of recording channels for magnetic recording. The 3480 uses a thin-film write head and a magnetoresistive read head to achieve a recording density of 972 flux changes per millimeter. This is a four-times increase in linear density over previous high-end digital-recording tape subsystems. The instantaneous data rate, three megabytes per second, is nearly three times the rate offered in previous IBM tape products. Increasing the data rate, reliability, and linear density placed severe requirements on the recording channel, head, tape, signal processing, and electronics. This paper describes the design objectives of the 3480 recording channel and the implementation of critical areas of the channel that were key to reaching the product goals. A brief description of the functions of a recording channel is included. Significant features of the 3480 write, read, and detection circuits are discussed.

error-correction coding [1]; and the modulation code that encodes each 8-bit byte into nine bits. The calculation is:

$$(972 \text{ K-bits/m-track})(2 \text{ m/s})[(18-4) \text{ tracks}](\text{byte}/9 \text{ bits}) = 3.024 \text{ MB/s}$$

The transfer characteristics of the MR read head ~~is~~ are shown in Fig. 2. Within the normal operating range A, a linear response to magnetic fields is maintained. If the magnetic field generated by the tape exceeds this limit,the signal is distorted, with high even-harmonic content. In conventional non-return-to-zero change-on-ones (NRZI) recording, for each 1 in the data there is a flux reversal, and no flux reversal for a 0. This method of recording, as shown in Fig. 3, generates a variety of frequencies depending on the digital sequences (patterns) recorded. The lowest frequency is caused by the sequence 10001 and the highest by an all-ones sequence. At the lowest frequency of the flux reversals generated by the 10001 sequence, the magnetic field is large enough to drive the operating point out of the linear range of the transfer characteristics of the MR head, causing severe second-harmonic distortion. To eliminate this problem, write equalization is used, where a flux reversal with half the regular pulse width is introduced for zeros. With double pulse writing,described later, this technique results in 972 fcmm for 1's and 1944 fcmm for 0's. The channel bandwidth is such that at 1944 fcmm the amplitude of the signal is so small that the operating point remains within the linear range, eliminating second-harmonic distortion. Figure 4 shows the waveforms required for double-pulse writing [2]. Using this method halves the write pulse width to 42.8 ns (85.7 ns/2). This reduction in pulse width places a stringent requirement on pulse location within the bit cell and relative location to adjacent bits. Any variation in bit location creates peak shifts on the read signal, reducing the margin for error in the detection of data.

In addition to enabling operation within the linear range of MR characteristics, the narrow pulses also help reduce power dissipation in the head.

continuous current large enough to produce the needed magnetic field would cause a prohibitive temperature rise at the write head. Experiments suggested by the Bauer-Mee model of the recording process [4] showed that the flux-reversal pattern produced by a pulsed write current (multiple overlapping write regions) was indistinguishable from the pattern produced by a constant write current. Thus, to control the temperature rise to an acceptable level, the 3480 uses a multiplexing scheme in which the head tracks are pulsed in six groups of three elements. The resulting power dissipation is six times less than the power dissipated using a continuous write current.

The write-pulse width is established by two factors: multiplexing and write equalization. The 3480 write equalization [2] requires that each bit be written to reduce the dynamic range of the readback signal. Each bit period of 514 nsec is divided into 12 time intervals. During the first six intervals, the first pulse of the bit is written for all 18 tracks, three tracks at a time. During the last six intervals, the second pulse of the bit is written, again three tracks at a time. The resulting pulse width for each bit is 43 nsec. Figure 5 shows a typical write pulse train derived from a NRZI recording input. With this approach, even-harmonic distortion is reduced by about 6 dB and power is reduced from about 3 to 0.5 watt on the head.

The amplitude of the write-current pulse is tightly controlled to maintain satisfactory overwrite performance and interchangeability between transports. Normal variability between transports, heads, and circuits produces variations in the read signal-to-noise ratio. In the 3480, the write current is controlled such that sufficient SNR is maintained, without the use of an erase head, over the full range of component variability. The sensitivity to write-current variations is a reduction of about 2 dB per approximately 10% the amount of current variation with interchange and overwrite. Satisfactory overwrite performance is defined as the residual signal from previously written data to reduce SNR to less than 3 dB. Overwrite noise manifests itself as in-band noise and creates fast baseline shift responses to the read-back signal.

various write malfunctions to be undetected, the 3480 write circuits provide fault detection to ensure that each pulse is generated correctly. Fault detection also prevents excessive overheating of write circuits in the event of a failure. For example, if the write voltage regulator shorts, a sensor circuit signals the write control logic, which stops any future write operation. The write-circuit fault-detection circuitry also provides complete fault-isolation capability. When a failure occurs, the fault is not only detected, but an error code is sent to the drive-control logic to indicate which replaceable unit needs servicing. Fault detection is accomplished by comparing incoming data to the actual write waveform. If a miscomparison occurs, a fault indication is given.

Design of the Write Driver and the Regulator

The write circuits must maintain accurate control of the write current and generate very fast rise and fall times to produce a 220 mA, 43 nsec pulse to the inductive write head. This is required for reducing head power and even-harmonic distortion. The write driver and regulator designs are discussed in the following paragraphs.

The write drivers consist of a single saturating switch for each leg of each head element with a pullup resistor to an accurately controlled voltage source (Fig. 6). The value of the pullup resistor generates the desired rise and fall times, while maintaining sufficient damping to eliminate overshoot. The write drivers include the sensing circuits used for fault detection (Fig. 7). Each write-element leg is connected to a comparator that toggles a flip-flop for each properly generated pulse. The output frequency of the flip-flop is checked by external logic. If one flip-flop pulse is missed, a head or cable fault is detected. If two flip-flop pulses are missed simultaneously, a write-card fault is detected.

The write-voltage source is a precision voltage regulator that is disabled except during a write operation. The output voltage gives the desired write current. The regulator uses a series-pass transistor that is controlled by an

The most critical part of the preamplifier is the first amplifier and biasing stage because the first stage must amplify the MR output signal and bias while providing:

- Common-mode rejection
- Impact-noise rejection
- Write-feedthrough rejection
- Low intrinsic circuit noise
- Dc offset rejection.

The two dominant sources of noise from the MR head are Johnson noise and impact noise, both of which have common- and normal-mode (differential) components. The Johnson noise voltage is due to thermal agitation in the finite resistance of the head. Its frequency range is in band to the data and is 20-30 dB below normal signal levels. That portion of the noise that appears in common mode is rejected, to a great extent, by using a differential pair as the first stage; however, the normal-mode component sets the lower limit of the achievable noise figure. A trade-off is made between signal amplitude and Johnson noise, since signal amplitude varies directly as the resistance and the (rms) noise vary as the square root of the resistance.

Impact noise is generated whenever asperities or foreign particles in the tape strike the head. The impact produces a transient thermal gradient at the head, resulting in a relatively large change in resistance and consequent output-signal disturbance. The common-mode components of the disturbance are rejected as before. The frequency range is generally one order of magnitude below the in-band data spectrum (100 Hz to 25 kHz), and is as high as 15 times greater than the normal read signal (15 mV). This noise is rejected or its effect reduced by good preamp common-mode rejection and high-pass filtering. The frequency spectrum of the disturbance is generally an order of magnitude

The 3480 equalization circuits are designed to correct for losses in frequency and phase response at the head-tape interface (HTI) by providing the proper magnitude and phase compensation to the read-back signal. Losses at the HTI are mainly a function of:

- Frequency or phase response of the head
- Magnetic characteristics of the tape
- Azimuth error of the head
- Tape-to-head separation
- Density effects (bit crowding)
- Defects in the tape.

Figure 10 shows the HTI represented schematically. The concept of a head-tape transfer function is useful for obtaining the necessary equalizer transfer function. By measuring the head-tape transfer function, an ideal equalizer can be synthesized to provide the optimum signal waveshape at the detector.

The 3480 equalizer produces a "derivative" response (a derivative response translates the recorded flux transitions into peaks). A derivative-response equalizer is especially suited for improving detection during dropouts caused by tape asperities, by contaminants on the tape, or by other defects that produce abnormal head-tape separation and compensates for baseline shifts. Dropouts cause varying amounts of signal loss (a factor of 10 to 20 times reduction), mostly at high frequencies. The equalizer is optimized for best performance under dropout conditions by emphasizing high frequencies. The equalizer must also remove baseline wander from the read-back signal. Baseline wander is caused by the overwrite process and by impact noise generated at the MR head. It is a low-frequency-signal component; in the derivative-response equalizer, the low-frequency-signal components are positive and negative comparators at the point in time when a peak would nominally occur, as determined by the phase-lock-loop clock circuit. The sampling technique makes the detection process insensitive to erroneous peak information caused by intersymbol interference and in-band noise. The sampled outputs of the comparators are passed through a non-return-to-zero decoder circuit to produce clocked, NRZ data. The decoder further enhances detection reliability by incorporating an alternating-peak polarity algorithm. The algorithm requires that each valid peak have the opposite polarity of the previous peak; peaks that do not agree with the algorithm are ignored.

Tracking Threshold

Reliable data detection requires a high-performance tracking-threshold circuit. The tracking threshold generates a voltage reference used by the detector to determine when a peak occurs. The voltage reference is a percentage of the average peak voltage. The threshold must: (1) follow rapid variations in peak amplitude, (2) respond to asymmetrical signals, and (3) limit at a minimum level to prevent incorrect clock corrections.

The bandwidth required to follow rapid variations in peak amplitude dictates using a data-sampling technique to control the charge and discharge of the threshold-peak detector. Rapid response with minimum ripple is obtained by discharging and charging the peak detector in coincidence with signal peaks. Response to asymmetrical signals is achieved by using two independent thresholds, one for positive peaks and one for negative peaks. The threshold also contains a clamping circuit that holds the threshold outputs above a specified minimum level. The minimum level is set to avoid erroneous corrections to the clock frequency during severe dropout conditions.

Phase-lock Loop

The phase-lock-loop circuit serves to extract clock information from the analog signal for clocking the digital data. The phase-lock loop must compensate for velocity and acceleration of the tape while maintaining an

Error-condition pointers are used to indicate when a specific track has a high probability of detection error. The pointer information is relayed to the error-correction logic to enhance its correction capability. The pointer must be generated within a narrow timing window of the actual error occurrence for maximum correction enhancement. Pointers that occur within a specified window are called captures; those occurring outside the window or when an error has not occurred are called false pointers. The ultimate performance of the adaptive cross parity ECC [1] relies on a high capture rate. The false-pointer rate must be low so as not to call error-recovery procedures during data streams having no errors. The 3480 pointer circuit uses the positive and negative peak comparator outputs and measures their location and pulse width. If the location and width are outside allowable limits, a pointer is generated. These limits are adjusted dynamically using the tracking threshold. If the threshold cannot track a very fast dropout, the allowable pulse width is tightened; if a slow dropout occurs, the threshold follows the peak amplitude and the pulse width limit is relaxed.

This method of dynamically determining whether an error is occurring or is about to occur is extremely sensitive to overall system parameters and requires a minimum of hardware. With accurate pointer indications (greater than 80%) and low false pointers (less than 200%), system performance after ECC is improved by a factor of about 15 under severely stressed conditions.

Tone Detector

The tone detector identifies the presence of the tone character (...100000100000...) used in formatting the tape. Because the phase-lock loop is not in lock during a formatting character, the tone detector must use an asynchronous clock. The detector uses a digital bandpass filter to define the occurrence of tone. To maximize detection reliability, a majority circuit is used that requires tone signals simultaneously on widely separated tracks; therefore, format characters can be properly sensed during dropouts.

Derivative-response signal equalization was used to correct for losses in the magnetic recording channel and was optimized to reduce sensitivity to distortions that occur in defects. An analog-sampling-detection system with a tracking threshold was developed to be insensitive to erroneous peak information caused by amplitude variations, waveform distortion, and noise. Error-condition pointers are created from the read-back signal at the detector to enhance the error-correction capability of the system.

These recording-channel elements, combined with the head, tape, transport, and error correction circuits, provide a highly reliable recording system.

ACKNOWLEDGMENTS

The authors express their appreciation to the recording-channel electronics development team, whose efforts are realized in the 3480 recording channel.

LIST OF FIGURES

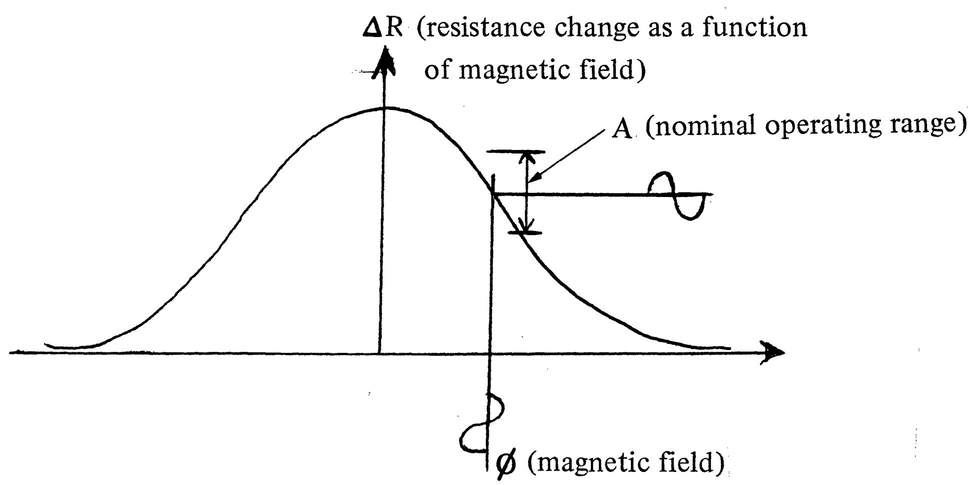

ΔR (resistance change as a function of magnetic field)
A (nominal operating range)
Ø (magnetic field)

Figure 2

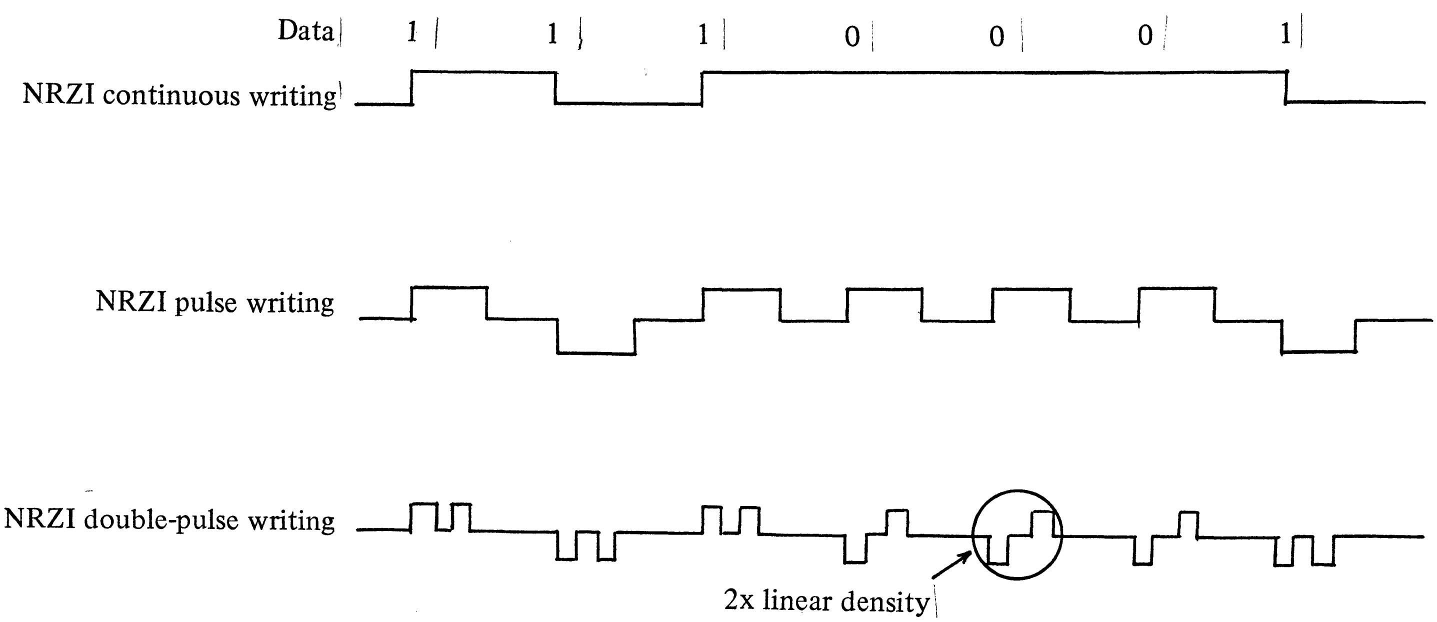

Data
1
1
1
0
0
0
1
NRZI continuous writing
NRZI pulse writing
NRZI double-pulse writing
2x linear density

Figure 4

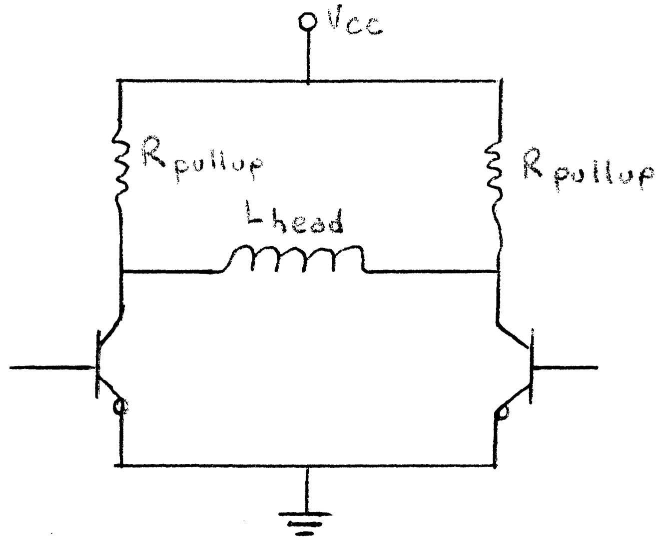


Figure 6

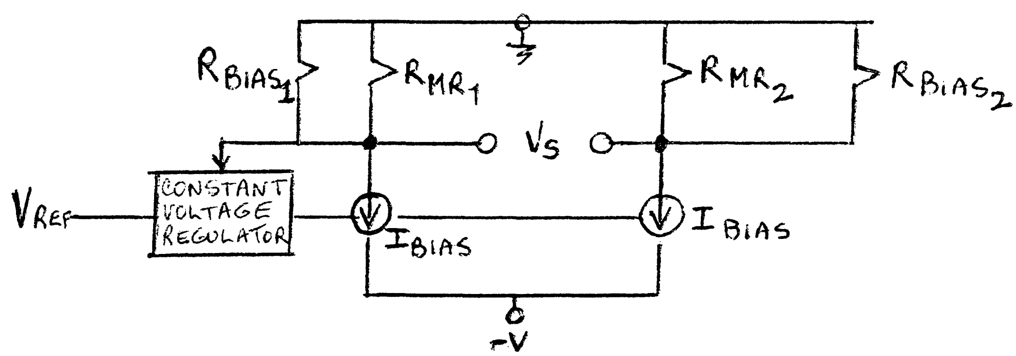
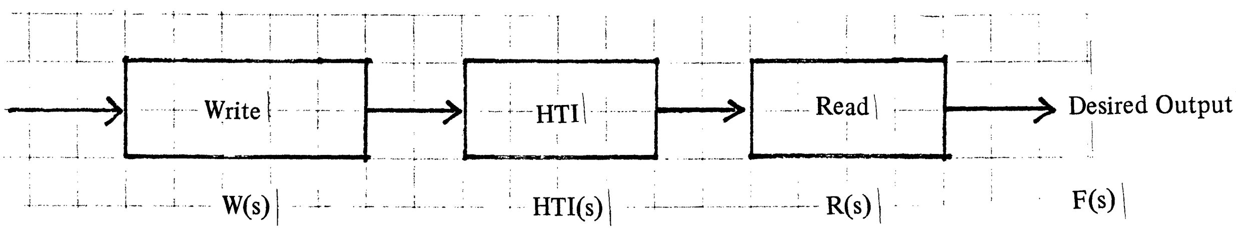

R BIAS 1
R MR 1
R MR 2
R BIAS 2
V S
V REF
CONSTANT VOLTAGE REGULATOR
I BIAS
I BIAS
-V

Figure 8



$$W(s)\,R(s) = F(s)/HTI(s)$$

Figure 10

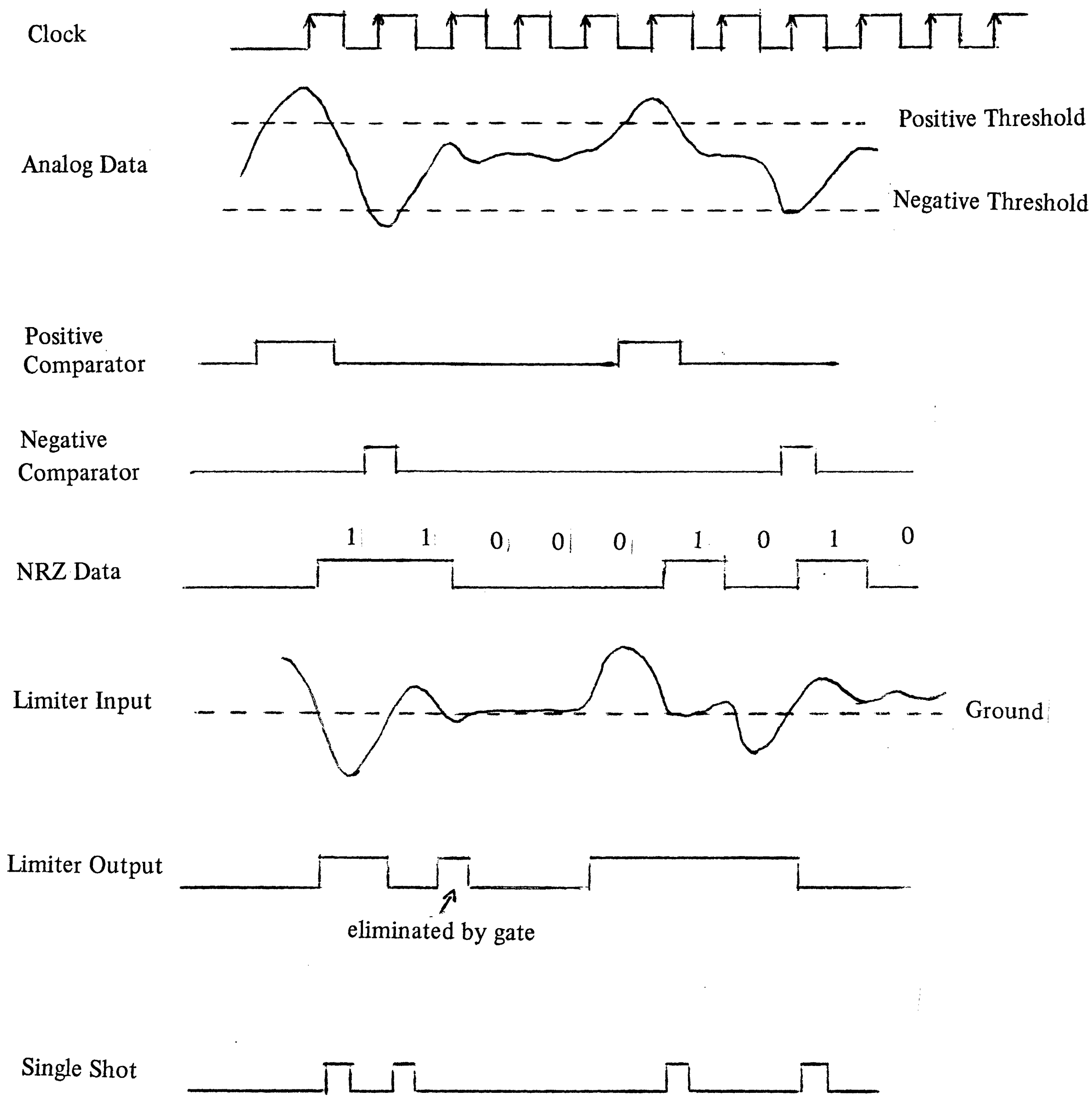

Clock
Analog Data
Positive Threshold
Negative Threshold
Positive Comparator
Negative Comparator
NRZ Data
1 1 0 0 0 1 0 1 0
Limiter Input
Ground
Limiter Output
eliminated by gate
Single Shot

Figure 12