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# FIBER-OPTIC COMMUNICATION SYSTEMS

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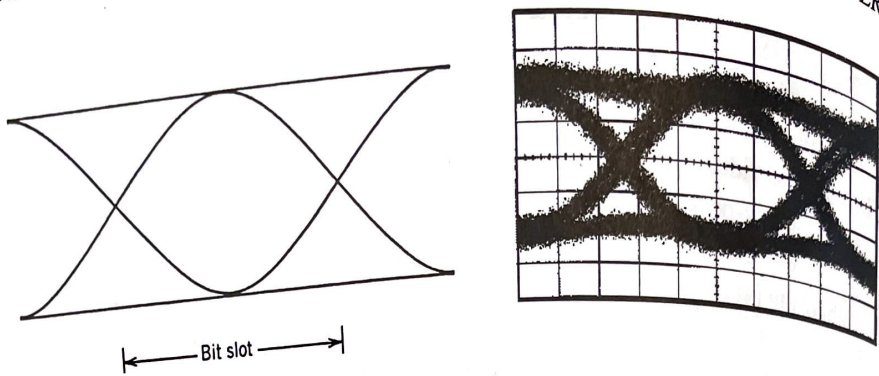


Figure 4.13: Ideal and degraded eye patterns for the NRZ format.

signal is maximum. At the same time,  $h_{\text{out}}(t) = 0$  for  $t = m/B$ , where  $m$  is an integer. Since  $t = m/B$  corresponds to the decision instant of the neighboring bits, the voltage pulse of Eq. (4.3.6) does not interfere with the neighboring bits.

The linear-channel transfer function  $H_T(\omega)$  that will result in output pulse shapes of the form (4.3.6) is obtained from Eq. (4.3.4) and is given by

$$H_T(f) = H_{\text{out}}(f)/H_p(f). \quad (4.3.7)$$

For an ideal bit stream in the nonreturn-to-zero (NRZ) format (rectangular input pulses of duration  $T_B = 1/B$ ),  $H_p(f) = B \sin(\pi f/B)/\pi f$ , and  $H_T(f)$  becomes

$$H_T(f) = (\pi f/2B) \cot(\pi f/2B). \quad (4.3.8)$$

Equation (4.3.8) determines the frequency response of the linear channel that would produce output pulse shape given by Eq. (4.3.6) under ideal conditions. In practice, the input pulse shape is far from being rectangular. The output pulse shape also deviates from Eq. (4.3.6), and some ISI invariably occurs.

### 4.3.3 Decision Circuit

The data-recovery section of optical receivers consists of a decision circuit and a clock-recovery circuit. The purpose of the latter is to isolate a spectral component at  $f = B$  from the received signal. This component provides information about the bit slot ( $T_B = 1/B$ ) to the decision circuit and helps to synchronize the decision process. In the case of RZ (return-to-zero) format, a spectral component at  $f = B$  is present in the received signal; a narrow-bandpass filter such as a surface-acoustic-wave filter can isolate this component easily. Clock recovery is more difficult in the case of NRZ format because the signal received lacks a spectral component at  $f = B$ . A commonly used technique generates such a component by squaring and rectifying the spectral component at  $f = B/2$  that can be obtained by passing the received signal through a high-pass filter.

The decision circuit compares the output from the linear channel to a threshold level, at sampling times determined by the clock-recovery circuit, and decides whether the signal corresponds to bit 1 or bit 0. The best sampling time corresponds to the situation in which the signal level difference between 1 and 0 bits is maximum. It

can be determined from the *eye diagram* formed by superposing 2–3-bit-long electrical sequences in the bit stream on top of each other. The resulting pattern is called an eye diagram because of its appearance. Figure 4.13 shows an ideal eye diagram together with a degraded one in which the noise and the timing jitter lead to a partial closing of the eye. The best sampling time corresponds to maximum opening of the eye.

Because of noise inherent in any receiver, there is always a finite probability that a bit would be identified incorrectly by the decision circuit. Digital receivers are designed to operate in such a way that the error probability is quite small (typically  $< 10^{-9}$ ). Issues related to receiver noise and decision errors are discussed in Sections 4.4 and 4.5. The eye diagram provides a visual way of monitoring the receiver performance: Closing of the eye is an indication that the receiver is not performing properly.

### 4.3.4 Integrated Receivers

All receiver components shown in Fig. 4.11, with the exception of the photodiode, are standard electrical components and can be easily integrated on the same chip by using the integrated-circuit (IC) technology developed for microelectronic devices. Integration is particularly necessary for receivers operating at high bit rates. By 1988, both Si and GaAs IC technologies have been used to make integrated receivers up to a bandwidth of more than 2 GHz [53]. Since then, the bandwidth has been extended to 10 GHz.

Considerable effort has been directed at developing monolithic optical receivers that integrate all components, including the photodetector, on the same chip by using the *optoelectronic integrated-circuit* (OEIC) technology [54]–[74]. Such a complete integration is relatively easy for GaAs receivers, and the technology behind GaAs-based OEICs is quite advanced. The use of MSM photodiodes has proved especially useful as they are structurally compatible with the well-developed *field-effect-transistor* (FET) technology. This technique was used as early as 1986 to demonstrate a four-channel OEIC receiver chip [56].

For lightwave systems operating in the wavelength range 1.3–1.6  $\mu\text{m}$ , InP-based OEIC receivers are needed. Since the IC technology for GaAs is much more mature than for InP, a hybrid approach is sometimes used for InGaAs receivers. In this approach, called *flip-chip OEIC technology* [57], the electronic components are integrated on a GaAs chip, whereas the photodiode is made on top of an InP chip. The two chips are then connected by flipping the InP chip on the GaAs chip, as shown in Fig. 4.14. The advantage of the flip-chip technique is that the photodiode and the electrical components of the receiver can be independently optimized while keeping the parasitics (e.g., effective input capacitance) to a bare minimum.

The InP-based IC technology has advanced considerably during the 1990s, making it possible to develop InGaAs OEIC receivers [58]–[74]. Several kinds of transistors have been used for this purpose. In one approach, a *p-i-n* photodiode is integrated with the FETs or high-electron-mobility transistors (HEMTs) side by side on an InP substrate [59]–[63]. By 1993, HEMT-based receivers were capable of operating at 10 Gb/s with high sensitivity [62]. The bandwidth of such receivers has been increased to >40 GHz, making it possible to use them at bit rates above 40 Gb/s [63]. A waveguide