Chapter 4

Optical Time-Division-Multiplexing Transmission System

4-1 Introduction

Development of ultrahigh bit-rate telecommunication is requisite for growing demand for expanded transmission capacity. To satisfy these demands, high-speed and wide-band electronics in photonic transmitters and receivers for multigigabit-per-second pulse-code modulated (PCM) systems is indispensable. The bit rate of electrical time-division-multiplexing (ETDM) system is current limited to 100 Gbit/s. System speed is mainly limited by the speed of the electronic circuits used. Although individual chips have been developed at higher data rate, these are only used in laboratory presently and methods of packaging have yet to be solved. One method to overcome this electronic speed bottleneck is to extend the well-known techniques of electrical multiplexing into the optical domain. Optical multiplexing technology is developed in recently years, and it can offer advantages, such like: enabling simple mux/demultiplexing and removing the need to electronically process all traffic entering a node. The two main approaches to optical multiplexing are optical wavelength-division [61] (or frequency-division [62]) multiplexing and optical time-division-multiplexing [63, 64]. In the medium term, WDM is a passive technique of combining a number of wavelengths to obtain very high capacities. However, although WDM is simple in concept, the effect of dispersion, passband of concatenated optical amplifier, and fiber nonlinearity, such as stimulated Raman Scattering (SRS), four-wave-mixing (FWM). Such the effects limit the number of wavelength channels and the transmission distance. An alternative, longer term approach is to use Optical time division multiplexing (OTDM) [65-68]. This approach uses a single wavelength to carry capacities of at least 40 Gbit/s. This permits the use of soliton transmission which simultaneously overcomes the harmful effects of dispersion and nonlinearity. Short optical pulses are used in a Return-to-Zero (RZ) data transmission format with temporal interleaving to map a number of optical data channels into a single electronic clock cycle. OTDM offers system design flexibility, including the possibility of adjustable bandwidth allocation in different baseband channels and the possibility of simple system hardware in which only a single transmitter laser is required for all channels.

OTDM was first demonstrated as early as 1968 [63], primarily as means to increase the capacity of an optical link. The research of optical time division multiplexing and demultiplexing for very high bit-rate PCM systems has been demonstrated for more than three decades [69-72]. Technical progress has continued, with the world’s first 40 Gbit/s experiments carried out using OTDM [73]. To achieve the 40 GHz repetition rate, source based on soliton are particularly attractive because of their simplicity and stability. Soliton pulses can arise in the anomalous dispersion regime due to nonlinear fiber propagation, and it can be described by the nonlinear Schrodinger equation (NLSE). Soliton sources at 40 GHz were already demonstrated [74]. For OTDM applications, this source would need pulse compression since 160 Gbit/s requires pulsewidth values lower than around 1.56 ps. Indeed, pulse compression might be adopted by another soliton-based technique.

4-2 High Speed Laser Source

In order to increase the bandwidth employment, high-repetition-rate short-pulse laser sources are essential for OTDM system application [75]. The signal pulses used in high-speed OTDM transmission must satisfy several requirements, the first of which is the pulsewidth. In OTDM transmission, the pulsewidth of the optical signal determines the upper limit of the bit rate and the pulsewidth of the optical signal pulses must be less than the time slot of the bit rate. In general, the requirements become more critical when the distance of transmission system is increased. For example, although a duty cycle of 3:1 may be sufficient to transport data over a few hundred km, but may not work over 1000 km where a duty cycle of better than 4:l would probably be required. The second requirement is the spectral characteristics of the short-pulse laser sources. The spectral width of the optical signal determines the fiber dispersion, it will limit the transmission length. Therefore, the spectral width should be as narrow as possible for a given pulsewidth. Transform-limited (TL) optical pulses are most adequate for this purpose because they have the minimum possible spectral width and can minimize the influence of dispersion in transmission fiber. The third requirement is synchronization to a master oscillator to realize synchronized transmission systems with a digital hierarchy. Another requirement is stability of the short-pulse laser sources.

To date, optical short pulses synchronized to a master clock have been generated by various methods such as gain switching [76–80], external modulation of a CW light by an electro-absorption modulator [81–84], and mode-locking [85-89]. Harmonic mode-locked fiber ring laser is one of various attractive optical sources for very high-speed optical transmission systems. These sources often use erbium-doped fiber amplifiers (EDFAs) as the gain medium and $LiNbO_3$ modulators for mode-locking, in ring configurations [90-93] and nonlinear compression schemes for pulse shortening at the output [90]. The merit of this kind of laser is almost TL picosecond pulses are generated without the need for any pulse compression scheme, but they are relatively complex, requiring additional component to ensure stability against fluctuation of the cavities due to environmental perturbations. Repetition rate multiplication can also be achieved by detuning the external signal frequency so that it satisfies the condition Eq. (2-23). With this technique the source mode-locks in a repetition rate equal to Eq. (2-23) and has been recently referred to as rational harmonic mode-locking.

4-3 OTDM Multiplexing and Demultiplexing

The basic principle of time-division multiplexing and demultiplexing is that each of the baseband data streams is allocated a series of time slots on the multiplexed channel. A multiplexer (MUX) assembles the higher bit-rate bit stream from several baseband streams and a demultiplexer (DEMUX) reconstructs bit streams at the original lower bit rate by separating bits in the multiplexed stream. The techniques for this process are well established for electrical time-division multiplexing and demultiplexing but are only now emerging in optical systems.

Fig. 4-1 shows a schematic of an *N* channel OTDM transmission system. A train of picosecond (ps) duration optical pulses from a suitable laser source is split N ways. Each optical pulse train is individually modulated by an electrical data signal forming in *N* optical RZ format data channels. Each of branches is delayed by a fraction of the clock period and synchronized to allow passive multiplexing to sum up an individual data stream. Here, the multiplexer is most simply implemented using passive fiber couplers with appropriate optical delays between the channels. To avoid crosstalk between these interleaved channels, the laser source must be able to generate optical pulses of duration < *1/N* of the clock period. Here, we design different length of fiber in each channel to delay the optical pulse trains. To multiplex an optical signal with period T ps to channel N, the required time delay $\Delta\tau_i$ for each path is:

$$\Delta\tau_i = i \times \frac{T}{N}(ps),\ i = 1,2,...,N-1 \tag{4-1}$$

And, from the formula:

$$\Delta L_i = \Delta\tau_i \times \frac{c}{n},\ i = 1,2,\ldots,N-1 \qquad (4\text{-}2)$$

The timing scheme is shown on Fig.4-2. We can obtain the required difference of the fiber length ΔL_i to cause the corresponding time delay in each path. ΔL_i is the difference of the fiber length for ith path. $\Delta\tau_i$ is the time delay for ith path. c is the speed of light in vacuum. N is the refractive index of the fiber core. The difference of the difference of the fiber length ΔL_i and time delay $\Delta\tau_i$ is in terms of the first path. For example, for multiplexing the optical pulse train of 10 Gbit/s to 40 Gbit/s, the period T is 25 ps, so the time delay is 3.125 ps, and the difference of the fiber length is 0.2 mm.

Optical amplifiers are used to maintain the correct signal power to keep sufficient signal to noise ratio for acceptable bit-error rate. In such systems, fiber dispersion can be managed in many ways. One method is to balance the average group velocity dispersion in the whole system such that it is zero referred to dispersion management and another is to use soliton transmission techniques. Demultiplexing and clock recovery allows the input optical signal to be split into the discrete channels.

4-4 Single-Channel OTDM Transmission

In this chapter, we simulate the single-channel OTDM transmission system of 40 Gbit/s, 80 Gbit/s and 160 Gbit/s and analyze performance of such high speed system.

A schematic diagram of the 40 Gbit/s transmitter is shown on Fig. 4-3 (a). The optical source is a RHMLFL, producing a continuous pulse train at a repetition rate of 10 GHz with a full width half maximum (FWHM) of 28 ps as shown on Fig. 3-2. After pulse compression, the FWHM of the pulse shortens to 1.5263 ps**.** The signal level is boosted in an erbium doped fiber amplifier (EDFA) before being split into four channels by a 1×4 optical power splitter. Each of the four 10 GHz repetition rate optical pulse trains is modulated individually from a 10 Gbit/s pseudorandom code generator using amplitude modulators to produce four 10Gbit/s optical RZ data streams. Different from the external modulation of a CW light source, the modulators are not being used to shape the pulses, but they are used as on/off switches. Before recombining the data streams using a 4 x 1 power splitter, each path passes through a variable delay line to interleave a single 40Gbit/s RZ data stream with the correct delay. Fig. 4-4 and Fig. 4-5 compare the optical pulse train of 10 GHz before and after multiplexing. The receiver shown in Fig. 4.3 (b) consists of an EDFA, an electro-absorption modulator (EAM), a pin photo diode, a low pass filter. The EAM is used to extract one of the four channels, which was then fed to the bit error rate tester (BERT).

When the bit rate of a single exceeds 40 Gbit/s, the third-order dispersion will influence the transmission system seriously. To solve this problem, we use DCF not only to compensate the second-order dispersion but also third-order dispersion of the SMF to extend the transmission distance in our system. The condition for a fiber link containing two kinds of fibers of length L_1 and L_2 to form the dispersion management is [94] :

$$\beta_{21}L_1 + \beta_{22}L_2 = 0 \tag{4-3}$$

and

$$\beta_{31}L_1 + \beta_{32}L_2 = 0 \tag{4-4}$$

Where β_{2j} and β_{3j} are second- and third-order dispersion parameters for the fiber of length L_j. The SMF has a second-order dispersion β_2 of -20.8 ps^2/km (dispersion coefficient $D = 16.75$ $ps/nm \cdot km$) and third-order dispersion β_3 of 0.1 ps^3/km. The second-order dispersion β_2 of the DCF is 117.9 ps^2/km (dispersion coefficient $D =$ -95 $ps/nm \cdot km$) and the length can be determined by Eq. (4-4) as 8.82 km. The third-order dispersion β_3 is decided by:

$$\beta_{32} = (\beta_{22}/\beta_{21})\beta_{31} = -(L_1/L_2)\beta_{31} \tag{4-5}$$

, and we chose $\beta_3 = -0.56\ ps^3/km$ to compensate the third-order caused by SMF.

The compensation configuration we use is post-compensation as shown in Fig. 4-6 and its’ dispersion map as shown in Fig. 4-7. The SMF exhibits an optical attenuation of 0.2 dB/km and the attenuation of the DCF is 0.6 dB/km. The parameters of SMF and DCF for simulation are listed in Table 4-1. The gain of the EDFA is 15.3 dB and its’ noise figure is 2 dB. Because the core of the DCF is smaller than SMF, the effective area is small. It leads to serious nonlinear effect. When the input power is large, the self-phase modulation (SPM) will mainly limit the transmission distance. However, when the input power is small, the signal to noise ratio (SNR) of the EDFA will be degraded and limit the transmission distance. Fig. 4-8 shows the Q factor versus input power of the SMF at received power of -33 dBm when the transmission distance is 294 km. We can find that when the input power is 6.05 dBm, the performance of the system is best. The back-to-back receiver sensitivity for a BER of 10^{-9} is -35.6 dBm. Transmission over 294 km with dispersion compensation induces a receiver sensitivity penalty of 0.7 dBm as shown in Fig. 4-9.

The 80 Gbit/s transmitter is the same as 40 Gbit/s except the number of the multiplexing channel is up to eight. It multiplex the optical signal from 10 Gbit/s to 80 Gbit/s as shown in Fig. 4-10. We also find the optimum input power of 3.69 dBm to balance the SPM effect and SNR of the EDFA as shown in Fig. 4-11. After transmission in 176 km dispersion compensated link, the receiver sensitivity for a BER of 10^{-9} is -33.5 dBm.

The power penalty at BER $= 10^{-9}$ due to 176 km transmission is 1 dB as shown in Fig. 4-12.

The 160 Gbit/s optical signal is generated by multiplexing 10 Gbit/s signal of sixteen channels as shown in Fig. 4-13. Fig. 4-14 shows the optimum power launched into SMF, the optimum value is -5.26 dBm. Fig. 4-15 shows the results of BER versus the received optical power. The receiver sensitivity for a BER of 10^{-9} is -14.8 dBm and induces power penalty of 0.7 dBm after transmission of 58 km.

4-5 Summary and Discussion

In this chapter, we have done the simulations of the single-channel of OTDM transmission system of 40 Gbit/s, 80 Gbit/s and 160 Gbit/s. The high order dispersion can not be ignored in such high transmission system and limits the transmission seriously. We use the dispersion compensating fiber to compensate the second- and third-dispersion caused by the single mode fiber (SMF). Because the effective area of the DCF is small, the SPM effect will worsen the optical signal and limit the transmission distance. However, small input power will degrade the SNR of the EDFA. We analyze the input power to obtain the best system performance. After optimizing the amplifier span, the 40 Gbit/s, 80 Gbit/s and 160 Gbit/s can individually transmit 294 km, 176 km and 58 km with power penalty 0.7 dB, 1 dB and 0.7dB for maintaining BER of 10^{-9}.

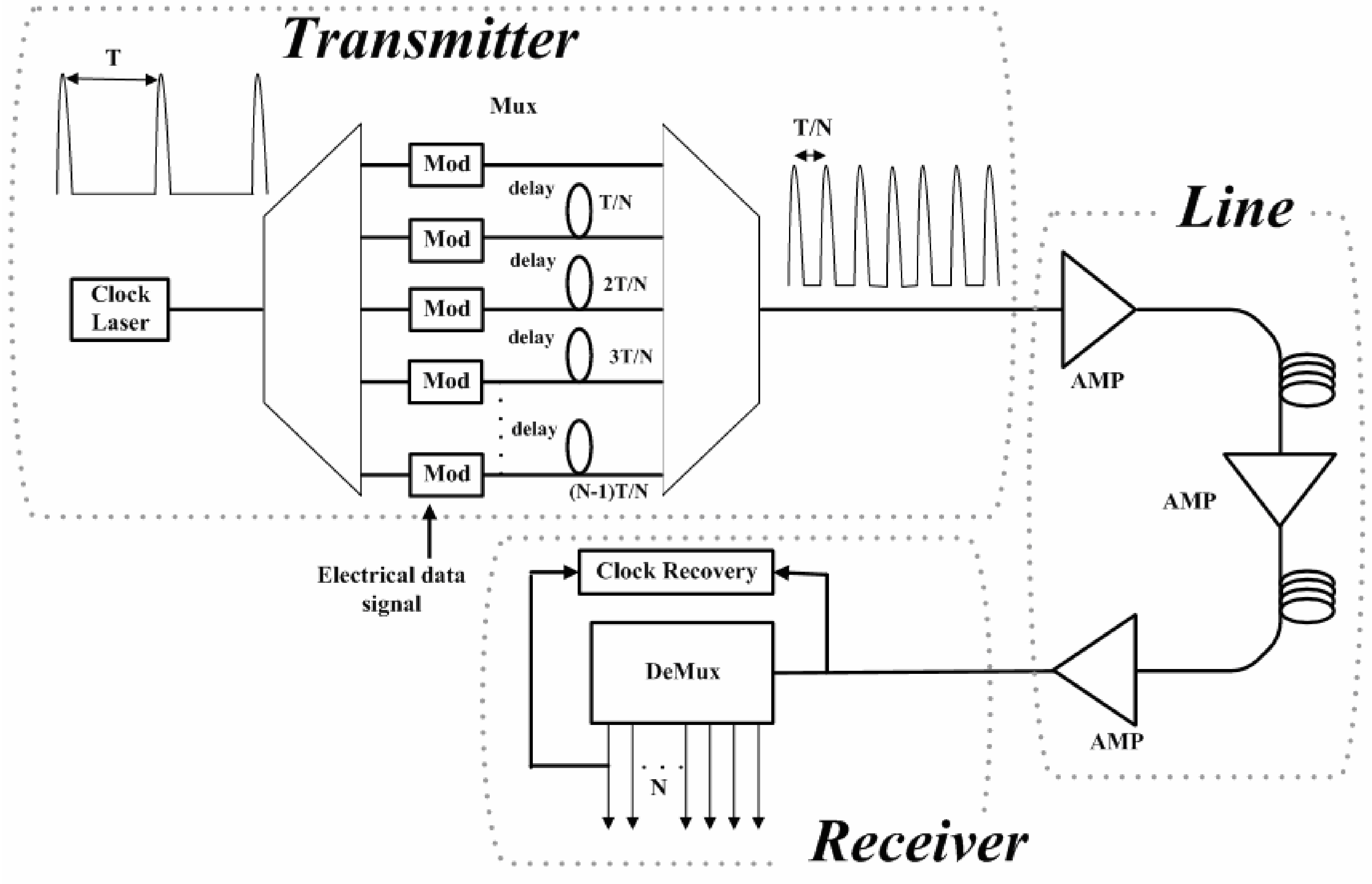


Figure. 4-1 Schematic illustration of a generalized OTDM transmission system.

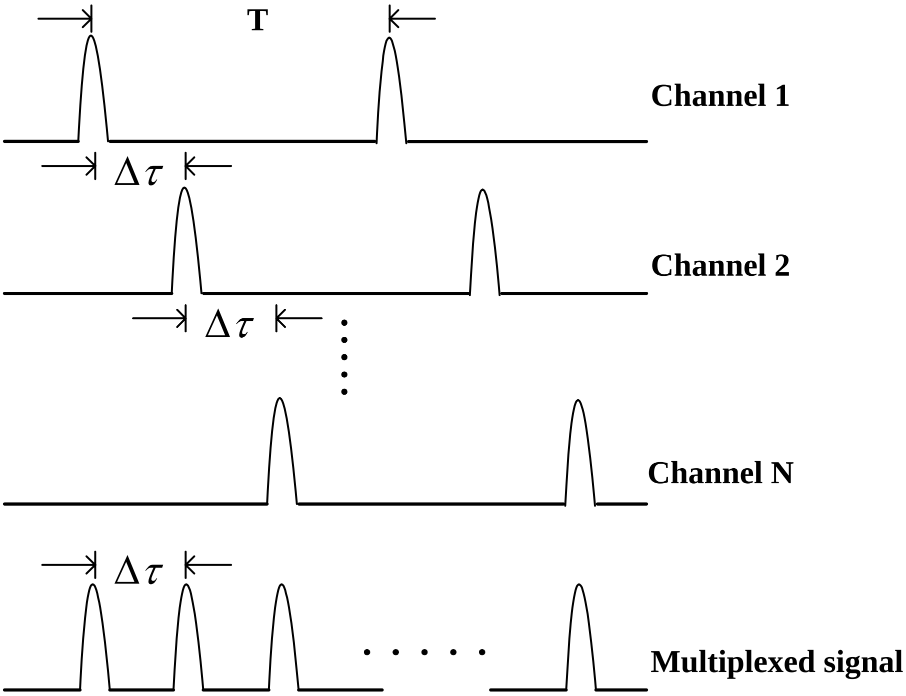
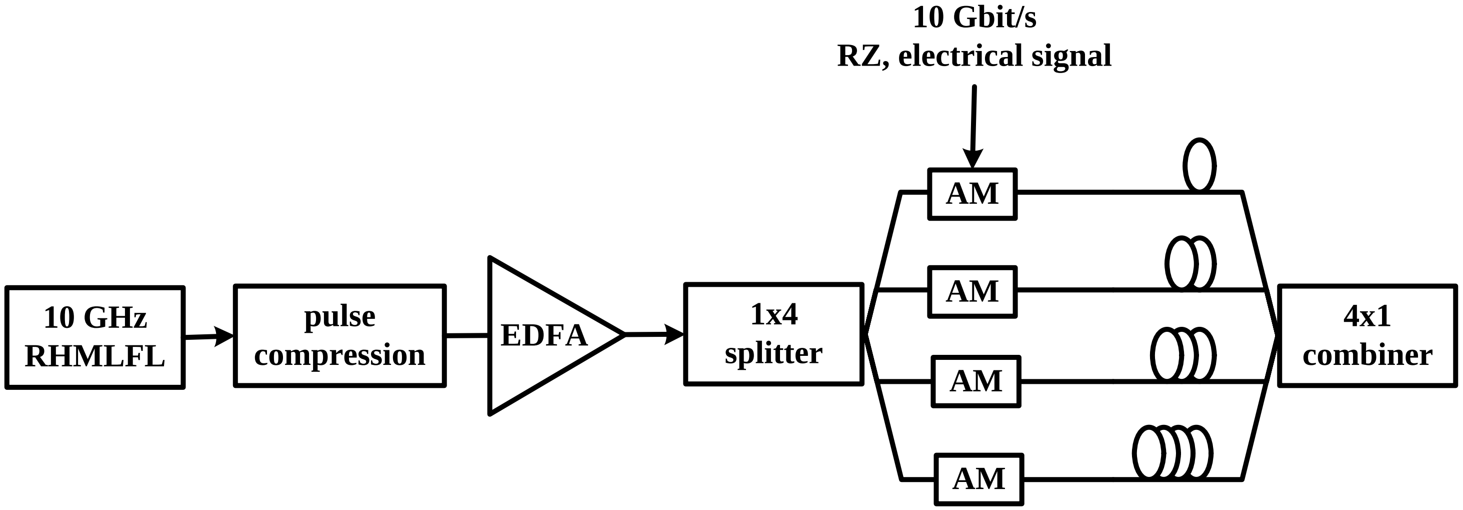
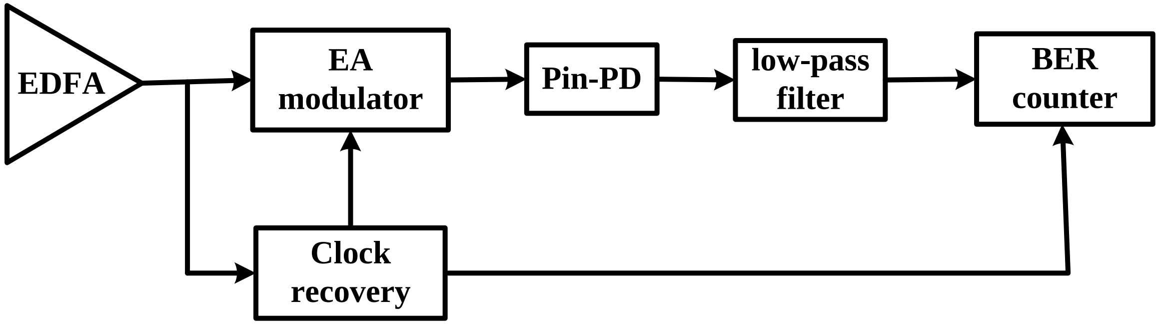


Figure. 4-2 Timing scheme for multiplexing in an n-channel OTDM.



(a) Transmitter



(b) Receiver

Figure. 4-3 (a) transmitter and (b) receiver of the 40 Gbit/s OTDM system

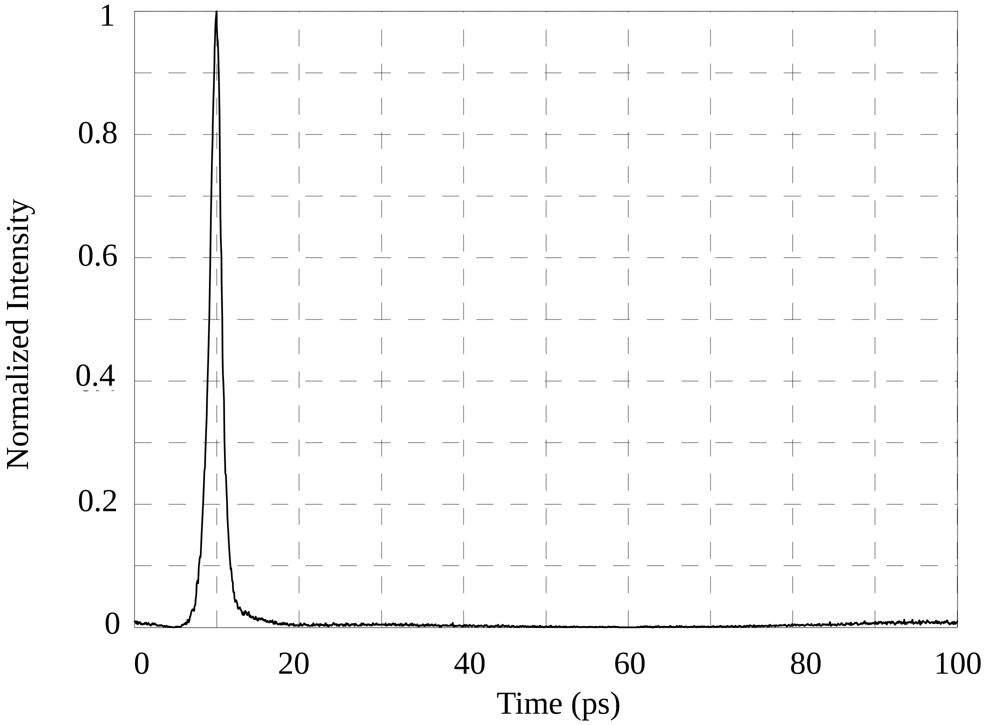


Figure. 4-4 10 Gbit/s optical pulse train before being multiplexed.

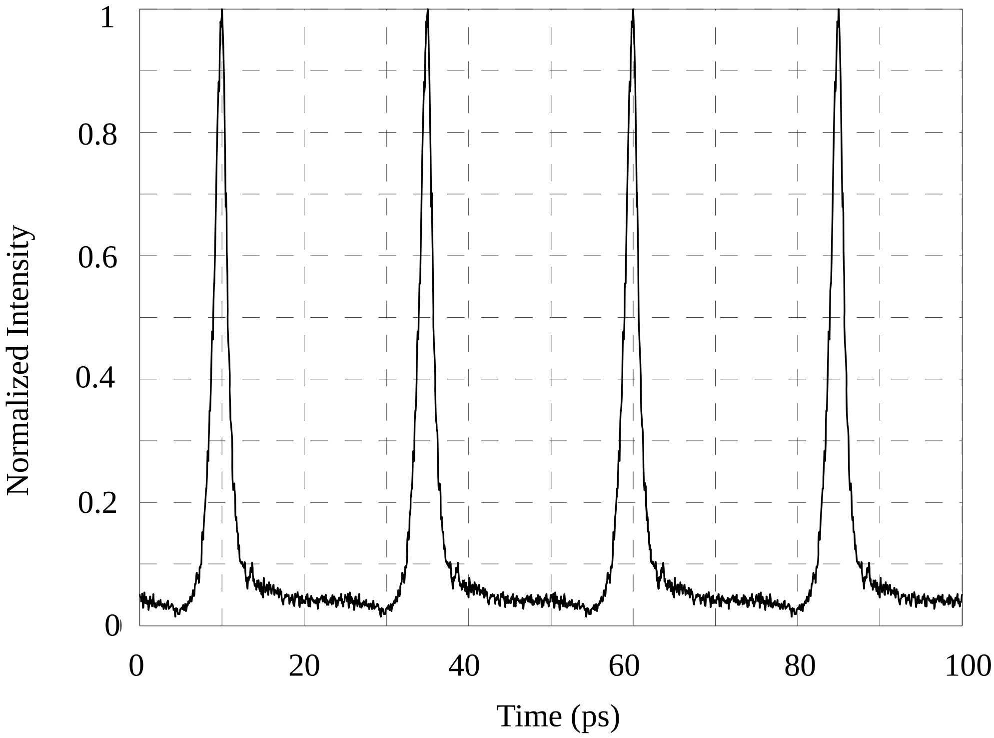


Figure. 4-5 40 Gbit/s optical pulse train after being multiplexed.

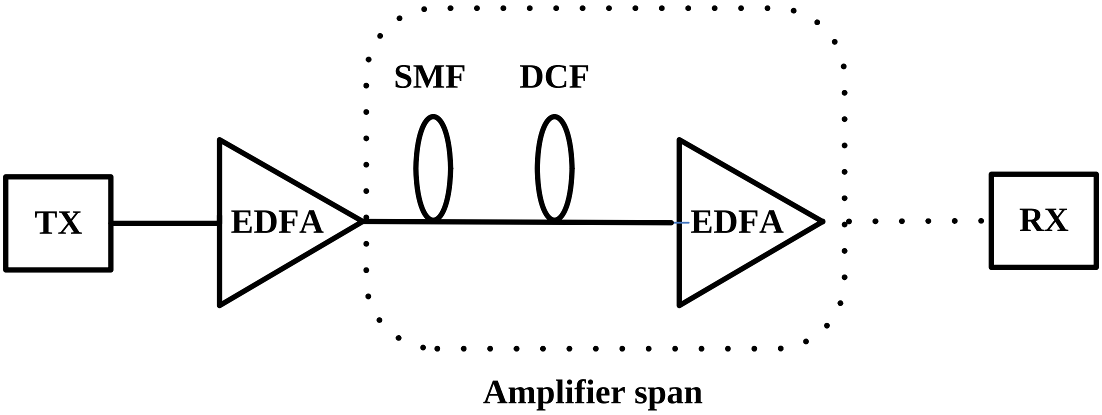


Figure. 4-6　Setup of the dispersion management.

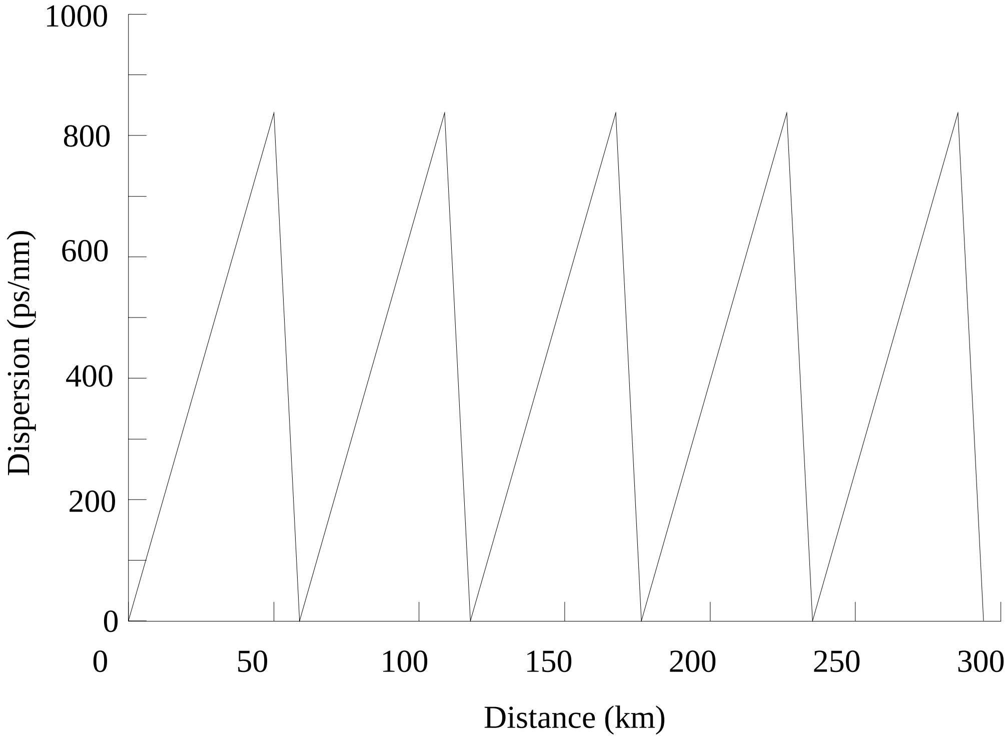


Figure. 4-7　Dispersion map of 294 km fiber link.

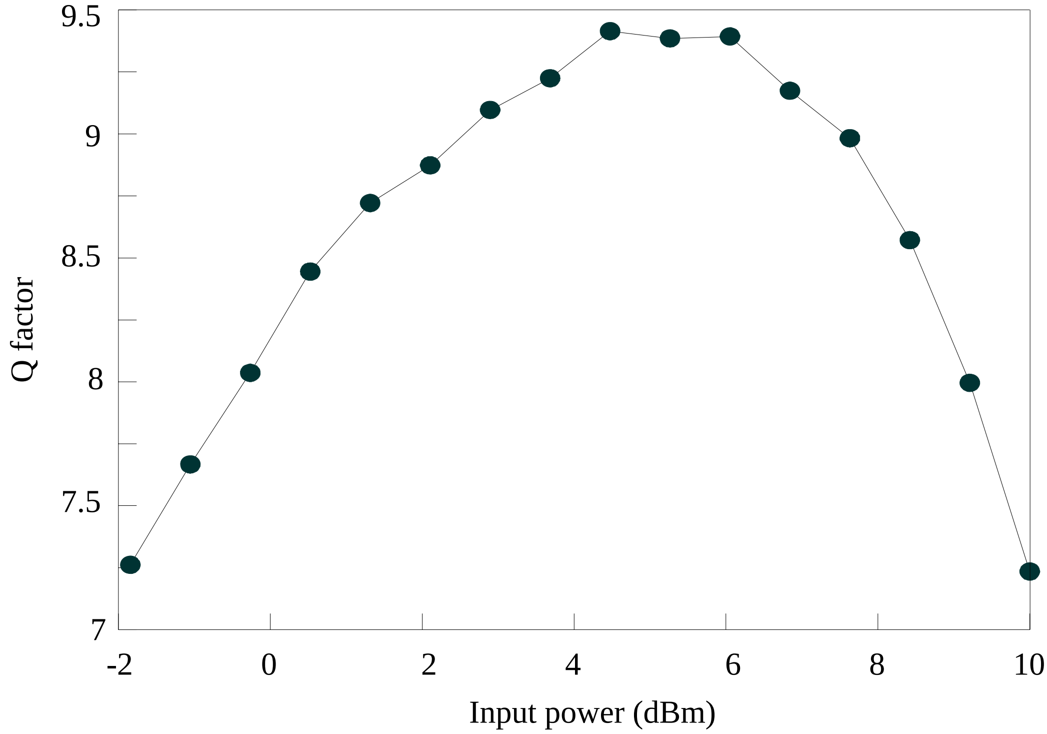


Figure. 4-8 Q factor versus different input power.

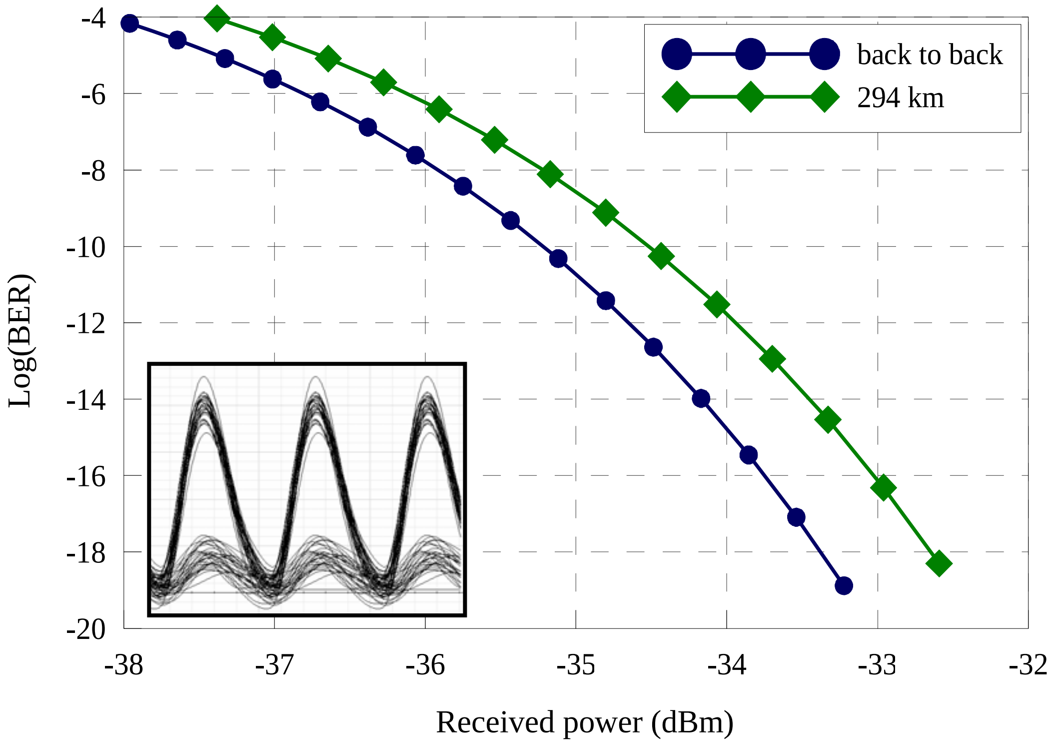


Figure. 4-9 BER versus received power and 40 Gbit/s eye after 294 km.

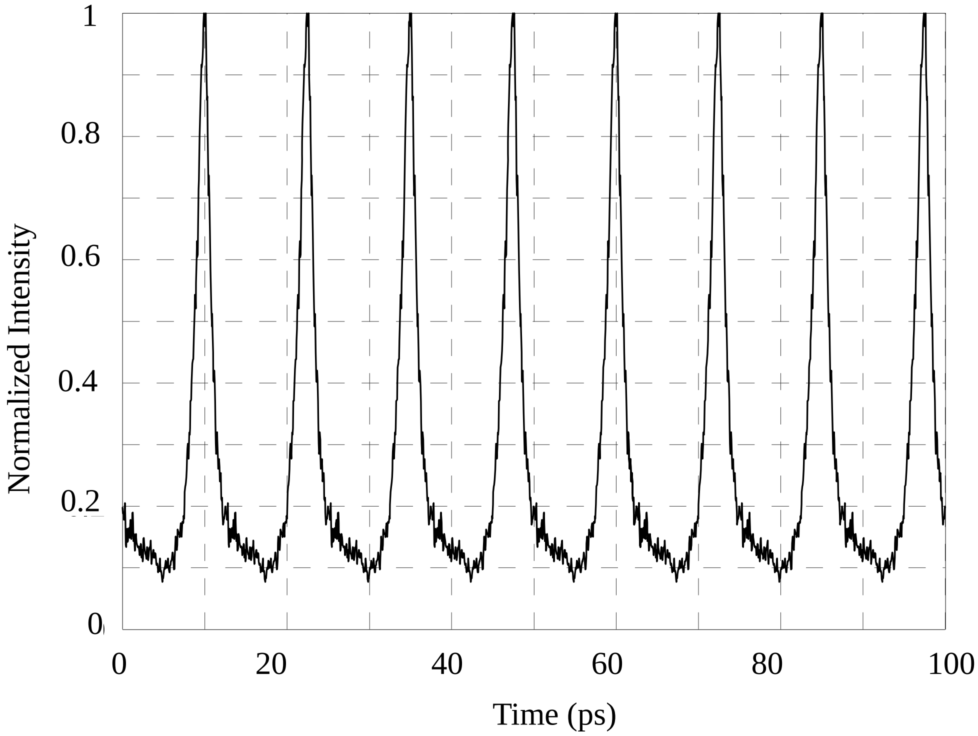


Figure. 4-10 80 Gbit/s optical pulse train after being multiplexed.

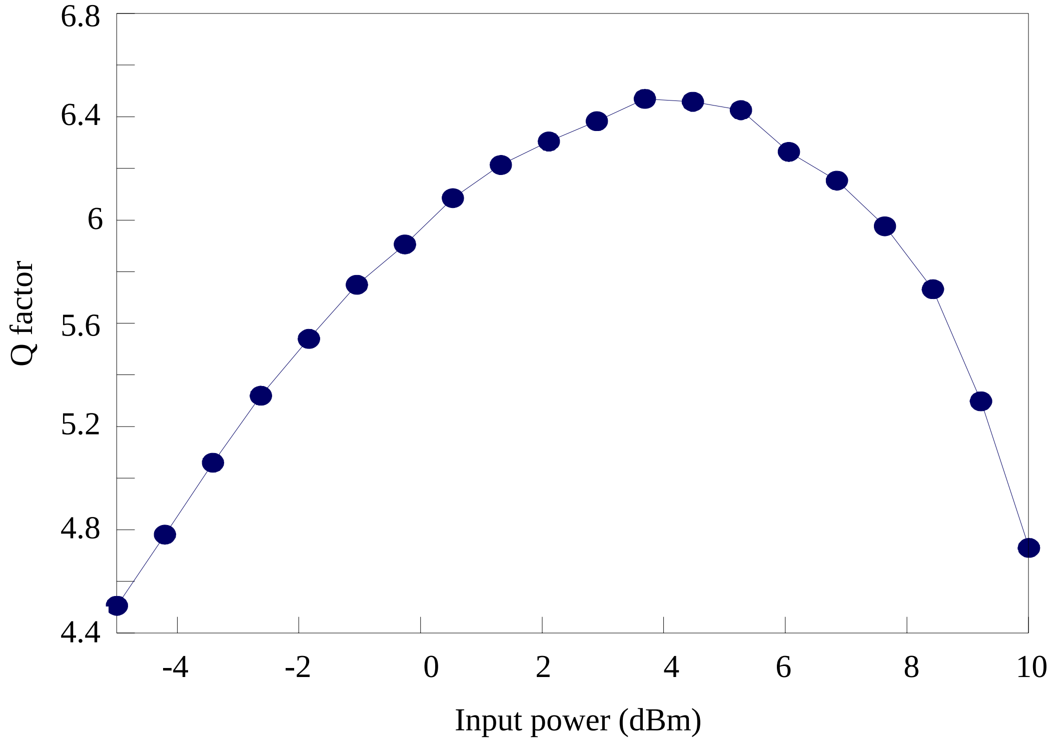


Figure. 4-11 Q factor versus different input power.

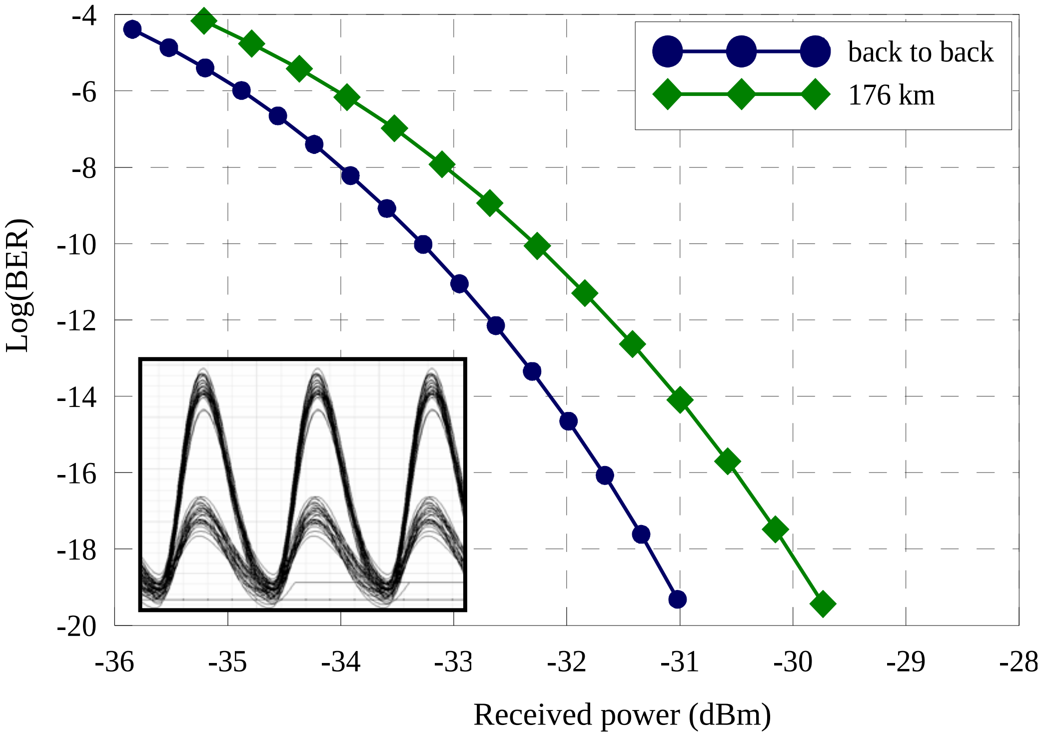


Figure. 4-12 BER versus received power and 80 Gbit/s eye after 176 km.

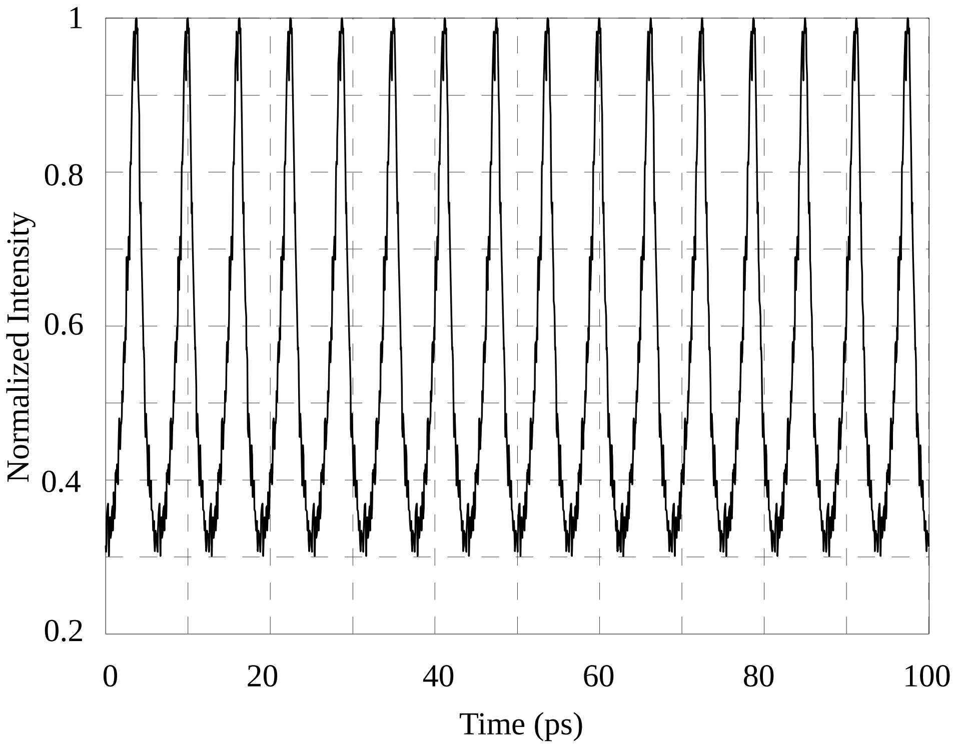


Figure. 4-13 160 Gbit/s optical pulse train after being multiplexed.

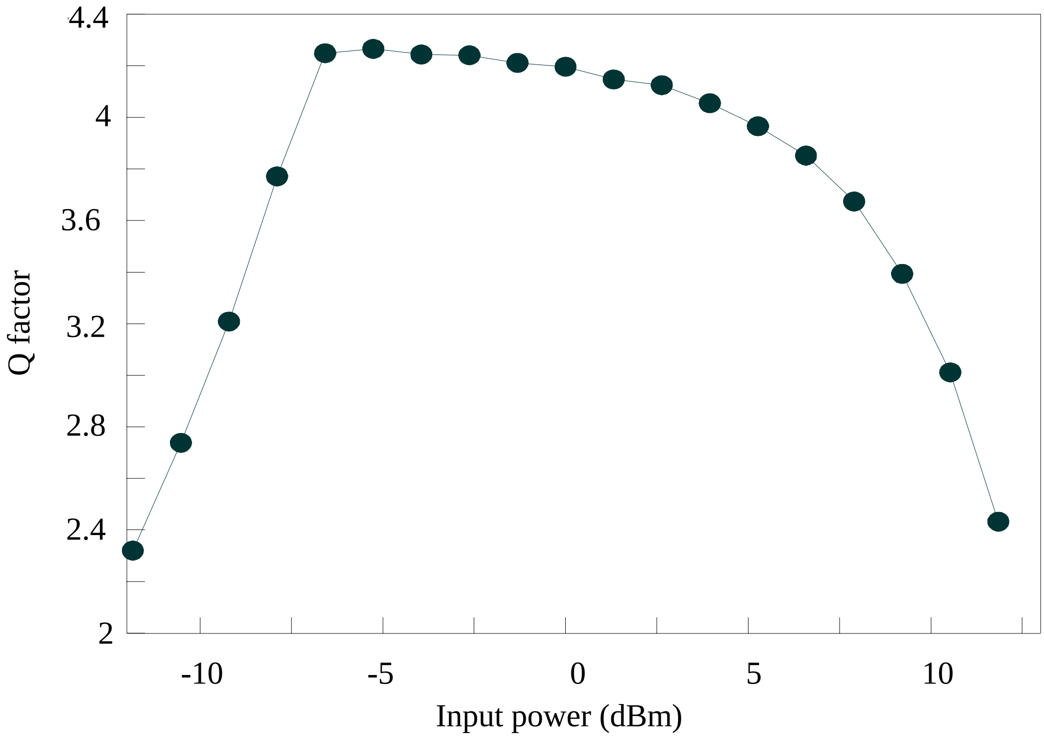


Figure. 4-14 Q factor versus different input power.

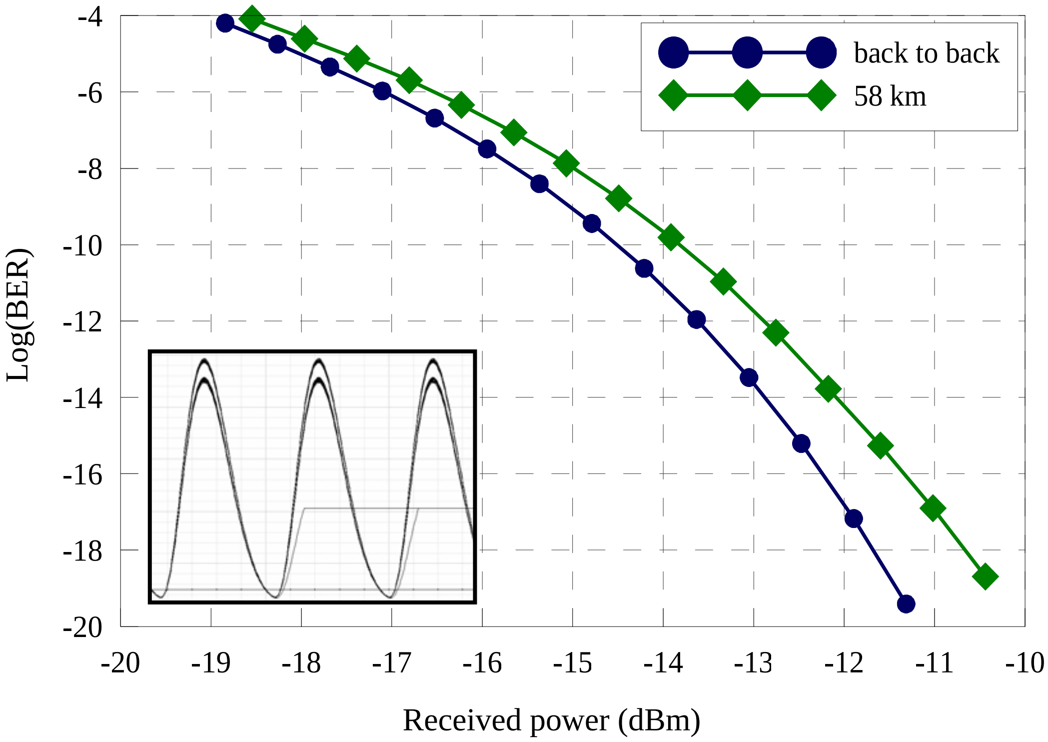


Figure. 4-15 BER versus received power and 160 Gbit/s eye after 58 km.

Table. 4-1 Parameters of SMF and DCF for simulation

Fiber Parameter	***SMF***	***DCF***
Length (km)	50 km	8.815 km
Fiber loss (dB/km)	0.2	0.6
Dispersion (ps/nm · km)	16.75	-95
Aeff (Effective Area) (μm^2)	80	30
n2 (Nonlinear refractive index) (m^2/W)	2.6×10-20	4.2×10-20
Second-order dispersion parameter (ps^2/km)	-20.79	117.9
Third-order dispersion parameter (ps^3/km)	0.1	-0.567