Chapter 1

INTRODUCTION

The era of electrical communications began with the advent of telegraphy. However, a single major event that considerably affected our world was the invention of the telephone in 1876 [1]. This event has drastically transformed the development of communication technology. The need to interconnect very large numbers of telephones has led to network topologies containing backbone routes capable of transporting large numbers of telephone conversations. In order to accommodate the increasing capacity of telephone networks, technology in transmission has been continuously developed. At first, wire pairs were replaced by coaxial cables to improve the capacity; however, that is still not sufficient. This led to the development and deployment of microwave communication systems. With the advent of digital transmission where voice and other forms of communication are transmitted digitally, a measure of system capacity is the number of bits per second that may be transported. In backbone systems a useful measure is the bit rate distance product a BL where B is the bit rate and L is the repeater spacing. The increase in the bit rate distance product BL through the advances in communication is shown in Fig. 1.1. It is seen that the most advanced microwave system in 1970 was able to operate at a BL product of around 100 Mb/s-km. Additionally, one may observe from Fig. 1.1 that the operating frequency has been continuously shifted to higher frequency to increase the BL product. This is because the available bandwidth and hence the maximum bit rate fundamentally depends on the magnitude of the carrier frequency. In metallic systems attenuation typically increases with frequency, which limits both the B and L that may be achieved. In free-space radio systems there is limited bandwidth that is available. In order to further support the demand in the BL product, it was necessary that the carrier frequency had to be higher to overcome the fundamental limitation. The next higher frequency band is in the region of light; thus, the field of "optical (fiber) communication systems" has emerged. As will be discussed below optical systems differ in several important regards from standard electrical (metallic and

wireless) systems; for example dispersion, non-linearity, and square law detectors. Signal design for such channels is the focus of this dissertation. But first we need to discuss briefly the basic elements of fiber optic systems.

1.1 EVOLUTION OF OPTICAL FIBER COMMUNICATION SYSTEMS

As their names implies, these kinds of communication systems use optical waves as carriers; hence, the bit rate-distance product BL can be improved several orders of magnitude compared to the microwave and coaxial systems as seen in Fig. 1.1 due to large available bandwidth and very low-loss of media. The most appropriate media that are used as channels in these systems are optical fibers, which were proposed in 1966 [2]. However, the first-encountered problem was that available optical fibers during that time had extremely high loss, exceeding 1000 dB/km. This problem challenged the researchers and engineers to find processes by which low-loss optical fibers could be fabricated. Finally, this problem was solved in 1970 when optical fibers having acceptable attenuation were first made[3].

The combination of low-loss optical fibers and the advance in semiconductor technology made optical fiber communication systems practically possible. In 1978, the first systems were commercially deployed. Their operating wavelength was at 0.8 μm, and they were capable of carrying data at the bit rate of 50–100 Mb/s with a repeater spacing of approximately 10 km [1]. As the technologies in optical-fiber fabrication as well as system components progressed, the BL product was increased continually. The progress in the bit rate-distance product BL of optical fiber communication system is shown in Fig. 1.2. It is usually divided into four generations [4], and they are briefly explained as follows.

1.1.1 First Generation

The first generation of optical fiber communication systems utilized multimode optical fibers and operated in the 0.8-μm wavelength region. The advantage of the multimode fibers is that their core is large; therefore, coupling of the light from the source into the fiber is not difficult. However, large core diameter also leads to an

unavoidable drawback. The optical waves travel in a multimode fiber with different paths; thus, they arrive at the receiver with different time delays, which causes pulse spreading. This phenomenon is generally termed multimode dispersion, also called intermodal dispersion.

In addition, there is another type of dispersion called intramodal dispersion or group-velocity dispersion (GVD). The intramodal dispersion results from the different spectral components of a signal traveling along an optical fiber with different speeds. Similar to intermodal dispersion, the intramodal dispersion causes pulse spreading. Both types of dispersion generate intersymbol interference (ISI), which limits the system performance. The bit rate-distance product BL of the first generation is therefore limited by both types of dispersion and fiber loss.

1.1.2 Second Generation

One approach to eliminate intermodal dispersion is to utilize a single-mode optical fiber instead of a multimode optical fiber. For this type of fiber, there is only one path (mode), in which the optical wave is allowed to travel; therefore, only chromatic (intramodal) dispersion exists. It should be noted that in single-mode operation an optical wave has two orthogonal polarizations (modes). Under the ideal condition at which the optical fiber is perfectly circular and the fiber material is isotropic, those two orthogonal polarizations would travel at the same speed. However, in practice the geometry of an optical fiber is not perfectly cylindrical, and the fiber material is anisotropic. This gives rise to polarization-mode dispersion (PMD) where two orthogonal polarizations (modes) of an incident optical wave travel at slightly different speeds [1]. In general the effect of PMD is negligible compared with the other types of dispersion.

When the attenuation of single-mode and multimode optical fibers is considered, the attenuation in the 1.3 μm wavelength region is less than that in 0.8 μm as shown in Fig. 1.3. However, another advantage of using the single-mode optical fiber is that this type of fiber has less internal (Rayleigh) scattering [5]; thus, the attenuation is also less than that of the multimode optical fiber. Note that the peak near 1.4 μm and a smaller peak near 1.23 μm seen in Fig. 1.3 are due to absorption caused by Hydroxyl (OH) impurities in the fiber [6]. In addition, a standard single-mode fiber (SSMF) exhibits

lowest dispersion in this new region. Both advantages led to the move of the operating wavelength from 0.8 to 1.3 μm resulting in higher BL product. With the advance in semiconductor technology, larger BL product of the order of 200 Gb/s-km was achieved, and it was primarily limited by fiber attenuation. At this figure of BL product, the undersea fiber optic system became feasible. The first transatlantic system called TAT-8 was implemented, and started operating in 1988 [7]. It consists of three pairs of single-mode optical fibers (one pair for backup purpose), and each pair operated at 296 Mb/s (one for each direction). It should be noted that the combined advantage of eliminating the intermodal dispersion and reducing the scattering loss by employing a single-mode optical fiber made the multimode optical fiber obsolete for long distance backbone systems. Thus, it was no longer used in systems where the BL product is large.

1.1.3 Third Generation

It is clearly seen from Fig. 1.3 that the attenuation of a single-mode optical fiber is lowest in the 1.55-μm wavelength window (0.2 dB/km). However, the chromatic dispersion of a standard single-mode fiber in this wavelength window is very large [+17 ps/(km·nm)], which is intolerable for very high BL systems. Note that the units of dispersion constant are ps of delay spread per km of transmission length, per nm of wavelength spread. In order to take the advantage of lowest attenuation at this wavelength window, narrow-linewidth lasers are required to minimize the effect of dispersion. Another approach is to employ a new type of fiber, known as a dispersion-shifted optical fiber (DSF) whose core-and-cladding profile is tailored so that the chromatic dispersion is minimum at the 1.55-μm wavelength region. This in effect allows the use of conventional lasers exhibiting relatively large spectral width (several nm). With both approaches, the bit rate-distance product BL of 500 Gb/s-km was achievable as shown in Fig. 1.2.

1.1.4 Fourth Generation

With the development of optical amplifiers, the significant improvement in the BL product became practically possible. The huge amount of bandwidth offered by the optical fiber could be fully utilized by using the wavelength division multiplexing

(WDM) technique. In addition, with the help of optical amplifiers all channels could be simultaneously amplified without optical-electrical-optical conversion; thus, the spacing between electrical regenerative repeaters could be extended considerably. As a result, the BL product was significantly increased, and can be larger than 100,000 Gb/s-km. There is another approach that can combat the dispersion effect. Such approach is to make use of fiber nonlinearity to balance the effect of dispersion, which results in the shape of optical pulses being preserved while traveling along the transmission link. The systems that utilize this technique are called soliton-based systems [8]-[10].

1.2 OPTICAL AMPLIFIERS

Before 1990s, the technology in fiber optic communication generally permitted only the use of a single wavelength in an optical fiber. There are several ways of expanding system capacity. The first is to use additional optical fibers, and another way is to increase the bit rate transmitted in each fiber. The latter is commonly referred to as time division multiplexing (TDM) upgrade. The first option does not create any difficulties as long as there are unused ("dark") fibers left. However, there are several factors that complicate the TDM upgrade. The increase in the bit rate results in higher required transmitted power and stronger effect of dispersion. Therefore, there are limitations in the extent to which the bit rate can be increased. Most importantly, for each TDM upgrade all in-line electrical repeaters have to be replaced to support the new bit rate, which may not be cost effective. Although the systems installed before the 1990s were not flexible, their high capacities compared to other media still made them economically attractive for high capacity applications.

Systems without intermediate electrical repeaters were realized when the erbium-doped fiber amplifiers (EDFAs) were developed in the late 1980s [11], [12]. The EDFAs can be employed as in-line optical amplifiers to periodically compensate for fiber attenuation; thus, electronic regenerative repeaters used for restoring the signal along transmission links are not necessary as long as the waveform distortion caused dispersion or the accumulated amplified spontaneous emission (ASE) noise from the amplifiers is not severe. In addition, optically boosting the signal power is bit-rate transparent and independent of the signal format, which provides flexibility in TDM upgrade.

Deployment of EDFAs also provides higher reliability than the electronic repeaters since the optical amplifiers requires fewer active components [13]. With EDFAs, the BL product can be improved dramatically.

However, for systems employing dispersion-shifted optical fibers, nonlinear effects become the major limitation. The most important nonlinear process is the four-wave mixing (FWM) where optical signals at different wavelengths are mixed together to generate new optical signals at new wavelengths; hence, the signal power of the main wavelengths is depleted and transferred to newly generated wavelengths [14]-[16]. It should be noted that the FWM process is similar to third order intermodulation distortion in electrical systems. Generally, the mixing of three signals to generate a new signal at different wavelength depends on the matching between relative-phase summation of two contributing signals, and that of another contributing signal and the resultant signal. For the FWM process to be strong the phase matching condition has to be satisfied, and that is easily obtained in the absence of dispersion. This is the case of systems employing dispersion-shifted fibers and the operating wavelength is in the vicinity of zero-dispersion wavelength to minimize the effect of dispersion. The four-wave mixing between the signal and the ASE noise depletes the signal power and instead increases the noise power, which in effect degrades the signal to noise ratio (SNR) [17]. Given a sufficient amount of dispersion, the phase matching condition can be avoided. Hence, there is the compromise between the effect of dispersion, and the nonlinear FWM. Despite this problem, the BL product is enhanced considerably by using EDFAs.

It is desirable that the transmission link has large local dispersion along the link to minimize the effect of nonlinearity while at the same time to minimize the pulse broadening effect caused by the dispersion. This desire seems unrealizable at first because large dispersion to minimize nonlinearity means severe pulse broadening. It should be noted that the effect of dispersion is a linear process; hence, it can be compensated although the nonlinear effect is not easily compensated. The ingenious technique to minimize the effects of dispersion and nonlinearity is to concatenate different types of optical fibers that have opposite chromatic dispersion. At any point along the link, the local dispersion is sufficiently large to make negligible the nonlinear effect. However, the end-to-end chromatic dispersion can be managed to zero to avoid

the effect of dispersion. This technique is generally known as dispersion management or dispersion map [18]-[22]. It should be noted that this technique is not perfect because nonlinearity cannot be compensated, and the waveform distortion caused by nonlinearity prevents the perfect removal of the effect of dispersion. Nevertheless, dispersion management is extremely beneficial. When it is combined with the EDFAs, the bit rate-distance product BL can exceed 40,000 Gb/s-km as shown in Fig. 1.2. This type of system is widely deployed in long-haul fiber optic systems, such as, TAT (Transatlantic Telephone)-12/13 [23], TPC (Transpacific Crossing)-5 [24], and ACPN (Asia Pacific Cable Network) [25] which services Asia-Pacific countries. In all of these systems, there are no electronic regenerative repeaters installed, and the distance between end terminals can be of the order of 8,000 km at a bit rate of 5 Gb/s.

1.3 WAVELENGTH DIVISION MULTIPLEXING (WDM)

Although the capacity provided by single-channel fiber optic systems is extremely high compared to the systems using other media, the traffic demand is also large and increasing every year. Transmitting only a single channel into an optical fiber seems to be extremely inefficient because the available bandwidth provided by an EDFA is around 40 nm extending from 1526 nm to 1566 nm, which corresponds to the available bandwidth of approximately 5 THz [26], and research is directed to further increasing this bandwidth. This huge amount of available bandwidth can be utilized to effectively expand the system capacity. By simultaneously transmitting multiples channels at different wavelengths the aggregated bit rate in a single fiber can be increased substantially. This method is generally called wavelength division multiplexing (WDM). At the transmitter side, multiple channels are multiplexed together by a WDM multiplexer and transmitted into a single optical fiber. All channels are simultaneously amplified by in-line EDFAs to periodically compensate for the fiber loss. At the receiver end, the transmitted channels are demultiplexed by a WDM demultiplexer, and fed to corresponding receivers.

One problem that had to be solved before WDM systems could be successfully deployed is that the gain profile of EDFAs is not uniform over the usable bandwidth, but rather it peaks around 1532 nm [27] as shown in Fig. 1.4. Although it is relatively flat

around 1.55 μm, a cascade of EDFAs would result in increasing the nonuniformity of the gain profile. Additionally, a chain of EDFAs causes reduction in the usable gain bandwidth due to self-filtering effect [28]. In WDM systems, the wavelength dependence of gain profile would lead to different SNR among channels. Such SNR differential might results in unacceptable performance in some channels. The narrow usable bandwidth means that fewer channels can be employed. Therefore, uniform gain profile and wide usable bandwidth is preferable. Various techniques to minimize the SNR differential and to enhance the gain bandwidth have been proposed. Some of them are discussed in the following subsections.

1.3.1 SNR Equalization by Pre-Emphasis Technique [28], [29]

This technique makes use of the fact that the SNR differential is due to channel-power discrepancy at the receiver, which can be compensated by adjusting the transmitted power as shown in Fig. 1.5. The procedure is to increase the transmitted power of channels that suffer small gain, and to decrease the transmitted power of channels that experience high gain. Equalization of powers or SNRs can be achieved by this technique; however, equalized SNRs are preferable because the performance depends on the SNR.

The main advantage of this technique is that it requires no modification of in-line EDFAs, and also does not depend on system parameters, such as amplifier gain, and link losses. Hence, it is an attractive solution for upgrading single-channel systems to WDM systems. The pre-emphasis technique requires only the values of unequalized SNRs in all channels at the receiver to compute the optimum transmitted power in each channel. That data can be sent back to the transmitter end via signaling channels that are generally included in high speed transmission systems. Another advantage is that the adjustment can be made in real time. However, the major drawback of this scheme is that the available transmitted powers have to be sufficiently large in order to cover the entire range of the required powers calculated to equalize the SNRs.

1.3.2 EDFA Gain Profile Optimization by Optical Filters

In this technique an optical filter is used for minimizing the wavelength dependence of the gain profile and for maximizing the usable gain bandwidth. The filter can be placed in the middle of the two-stage EDFA [30], [31], after the EDFA [32], [33], or after multiple EDFAs [34]. The transmission characteristic of the filter compensates for the wavelength dependence of the transmission characteristic of the EDFAs; hence, the overall transmission characteristic is flatter and broader than that without the filter. Many types of filters have been proposed in the literature; they include a Mach-Zehnder optical filter [32], Bragg-grating filter [33], and long-period grating filter [30], [31], [34].

The benefit of using optical bandpass filters is their reliability. This is simply because passive components are more reliable than the active ones. Among various types of optical filters the long-period grating filters are most promising due to their ease of fabrication, low cost, low back reflection, and low temperature sensitivity [31], [35]. In addition, the filter is all-fiber, which results in low insertion loss. The basic concept of the long-period grating is to scatter the light at specific wavelengths to the lossy cladding of the optical fiber. Such scattering can be accomplished by mean of periodic perturbation of the refractive index in the fiber core. By employing multiple gratings the transmission characteristic of the filter can be tailored to maximize the gain bandwidth and minimize the wavelength dependence of the EDFA gain profile.

Shown in Fig. 1.6 (a) is the schematic diagram of the dual-pumped EDFA employing the long-period grating filter [31]. The filter is inserted between two stages of EDF to equalize the gain spectrum, and the transmission characteristic is shown in Fig. 1.6 (b). The filter consists of three long-period gratings fabricated so that the combined transmission characteristic negates the wavelength dependence of the EDFA, hence maximizing the usable bandwidth. From Fig. 1.6 (c), it is clearly seen that the EDFA incorporating the long-period grating filter provides the gain of approximately 22 dB over a 40-nm bandwidth. This extremely wide bandwidth could considerably increase the throughput of the system.

1.3.3 WDM Development and Deployment

The early deployment of commercial multiple-channel systems dates back to the late 1980s. The system consisted of only two channels at 1.3 and 1.55 μm, each at the bit rate of 1.7 Gb/s [4]. At that time EDFAs were not available; thus, the regenerator span was limited to 50 km. As wide-band EDFAs, WDM (de) multiplexers and tunable lasers were continually developed, successful experimental demonstrations increasing the aggregated bit rate and channel count per fiber grew accordingly. Ultimately, the WDM technologies became sufficiently mature for commercial deployment, and the first terrestrial WDM system with optical amplifiers was deployed in 1995 [36]. It was the next generation lightwave network (NGLN) system, owned by AT&T, containing 8 WDM channels, each at the bit rate of 2.5 Gb/s. The regenerator span was 360 km, which was made possible by EDFAs. It should be noted that not only new systems could utilize WDM technique, but also the installed systems. By adding and upgrading equipment at end terminals, single-channel systems employing EDFAs could be upgraded to WDM systems to support the increasing demand in network capacity. This approach has been exploited in both terrestrial systems [37] and undersea systems [38], thus increasing the capacity of already-installed systems by many folds. For example, TAT-12/13 and TPC-5 systems, which were designed for single-channel operation and became operational since 1996, were upgraded to WDM systems two years later. During this time, the Internet and broadband access started to grow exponentially, which in effect has fueled the need for higher capacity network to support growing demand in the future. This has challenged researchers and developers around the world to improve system performance so that it could satisfy the demand.

The major experimental breakthrough came in 1996 when Terabit-per-second WDM was successfully demonstrated by various research laboratories [39]-[41]. In the experiment conducted by researchers at Fujitsu, 55 channels, each at the bit rate of 20 Gb/s, were successfully transmitted over a 150-km dispersion-managed transmission link Each span consisted of a 50-km standard single-mode fiber (SSMF) and a dispersion compensating fiber (DCF), and the amplifier spacing was 50 km. On the other hand, transmitting ten 100-Gb/s WDM channels through 40 km of dispersion-shifted fiber was demonstrated by NTT. The bit rate of 100 Gb/s per channel was achieved by optical time

division multiplexing (OTDM) ten 10-Gb/s channels. Note that OTDM is a preferred mean of multiplexing high-speed signals because the limitation in the speed of electronic devices. The polarization multiplexing technique was used by AT&T Bell Labs to achieve 1-Tb/s transmission. Twenty-five channels consisting of polarization-multiplexed fifty 20-Gb/s channels were successfully transmitted through 55 km of nonzero-dispersion fiber (NZDF) with a zero-dispersion wavelength of 1.513 μm and dispersion slope of 0.07 ps/nm^2/km. At the receiver end, a polarization beam splitter was used to separate two orthogonal channels at a given wavelength. It should be noted that the approaches in these experiments to achieve Tb/s systems were different. NTT had demonstrated the possibility of employing OTDM to increase the bit rate per channel whereas AT&T Bell Labs showed the potential of polarization multiplexing techniques.

1.3.4 Beyond Tb/s Era

Shown in Fig. 1.7 are the designated wavelength bands available for transmission, and types of optical amplifiers capable of operating in those bands. The designation of optical wavelength bands is similar to radio communication. C, L and S stand for conventional, long, and short, respectively whereas E and U stand for extended and ultra-long, respectively. Since the migration from 1.3-μm to 1.55-μm wavelength region, the first band that has been utilized is the C band. This is simply because in this wavelength band the fiber attenuation is lowest and because the gain bandwidth of EDFAs coincides with this band. The next wavelength band that was utilized is the L Band, which is made possible by the improvement in EDFA technology. Still, the combined wavelength range of both the C band and L bands is only a fraction of the low-loss window provided by an optical fiber, which extends from 1.45 to 1.65 μm over which range the loss is less than 0.3 dB/km [42]. In recent years, progress in optical amplifier technologies has grown rapidly, especially Raman amplifiers. This has enabled us to use other wavelength bands, such as S band and U band as shown in Fig. 1.7. In Raman amplification the energy is transferred from the pump signal to the desired signals due to the nonlinear Raman scattering in the optical fiber [43]. The most promising aspect of a Raman amplifier is that its gain spectrum can be located at any desired wavelength by carefully selecting the

pump wavelengths and pump powers [43], [44]. Thus, Raman amplifiers are promising for filling the wavelength gaps left by rare-earth-doped fiber amplifiers.

Enabling technologies in many areas of fiber optic communication have driven the growth of system capacity. Shown in Fig. 1.8 are the latest experimental achievements in optical fiber communication [45]. It is clearly seen that Tb/s capacity in a single fiber is not uncommon nowadays, and the bit rate-distance BL product can be over 20 Pb/s-km (Peta = 10^{15}). From Fig. 1.8 the trade-off between the aggregated bit rate per fiber and transmission distance is obvious. Shorter transmission distance is sacrificed for higher total bit rate per optical fiber or vice versa. The exploding increase in the system capability comes from many factors. Narrowband and precisely controlled filters and sources allow the increase in the number of channels transmitted. The improvements in optical amplifiers expand the usable bandwidth for transmission. Advances in semiconductor electronics enable us to increase the bit rate per channel. Currently, the trend in the bit rate per channel is to step from 10 Gb/s to 40 Gb/s with relative decrease in channel spacing to increase system capacity. As the channels are packed more closely together and the bit rate per channel is increased, the impairments caused by optical fibers become extremely severe, let alone the fact that those impairments increase with transmission distance. The undesired nonlinear interchannel interactions among WDM channels are more severe as those channels are packed closer together; however, those impairments can be suppressed with proper fiber configuration along the transmission link. The modulation format of the signal also plays an important role in expanding system capacity. With proper modulation format various impairments caused by nonlinearity and dispersion can be further minimized, which in effect maximizes system performance. This leads to the objective of this dissertation.

1.4 MOTIVATION FOR THIS DISSERTATION

In the past, the modulation format used in fiber optic communication was simply intensity modulation (IM), which is a very primitive way of transmitting data. Although IM is simple to implement, the signal is very susceptible to various impairments along the transmission path. Recently, it has been realized that alternative forms of modulation format should be utilized to improve system capacity so that it can catch up with the

exploding demand in network capacity. Here we focus on optical modulation formats based on return-to-zero (RZ) pulses because it has been shown that the use of the RZ signal format generally results in better performance than non-return-to-zero (NRZ) for transmission in nonlinear dispersive fiber [46]-[49]. By imposing some special characteristic onto the RZ signal, system performance can be greatly improved. For example, prechirping the pulse with the sign of chirp opposite to that introduced by the fiber dispersion can further enhance the performance due to pulse compression effect [50]-[52]. This is referred to as chirped-return-to-zero (CRZ). Experimental results [53]-[55] suggest that phase inversion of alternate pulses improves the performance by reducing the intersymbol interference. Although phase modulation is used in the transmitter, receivers are still square law detectors that are insensitive to optical phase. The purpose of phase modulation is to combat various impairments in an optical fiber. Note that alternate bit phase inversion removes the carrier component from the power spectral density (PSD) of the transmitted signal, and is consequently referred to as carrier-suppressed return-to-zero (CS-RZ).

It is clearly seen that phase modulation at the transmitter is a key factor that leads to performance improvement. However, we have found that the filter at the transmitter is also essential to maximize system performance. Three types of synchronous phase modulation are studied in this dissertation: square-wave phase modulation (180° phase shift between alternate bits), sinusoidal alternating-phase modulation (modulation frequency of half the bit rate), and sinusoidal same-phase modulation (modulation frequency of the bit rate). Our initial investigation is focused on how phase modulation and filtering at the transmitter improves the performance of systems employing the RZ signal format. It is found that each type of phase variation has its own mechanism that yields performance improvement. Our results indicate that there are three separate mechanisms: pulse compression, pulse peak intensity enhancement, and spurious pulse suppression.

It should be noted that synchronous phase modulation at the transmitter is not the only approach to apply some useful phase characteristic on to the signal. Encoding the original data can also put some special phase property on the signal. Recently, it has been shown that alternate mark inversion (AMI) signal format, which is a variant of duobinary,

possesses an additional phase property that CS-RZ does not have [56]. Thus, we also investigate the performance of the AMI signal format. It should be noted that the implementation of AMI is completely different from the other signal formats employing synchronous phase modulation, which we previously considered.

In addition to evaluating and comparing various techniques proposed in the literature, we also propose a new technique that can generate RZ pulse trains suitable for optical transmission. It is accomplished by modulating the continuous-wave (CW) signal by a square-wave (SW) phase function, and then filtering that signal. It turns out that the RZ pulse train generated from this technique has several special features that improve system performance. We term this signal format continuous-wave square wave (CWSW). The most important feature of this signal format is a phenomenon called peak intensity enhancement (PIE). In general the fiber dispersion broadens a pulse as it travels along an optical fiber. This is still true for the CWSW pulse; however, the peak of the CWSW pulse initially increases and then decreases during the propagation due to the nature of the pulse shape. This in effect provides an additional improvement, which we will see later in this dissertation.

The main objective of this dissertation is to investigate and analyze limitations and advantages of various optical modulation formats. Our main focus is on the comparisons between our proposed signal format and the other formats on single-channel systems. Since this investigation is at the system level where there are many system components involved, it is difficult to find a closed-form expression that fully describes system performance. The split-step Fourier (SSF) simulation [57] is utilized to investigate system performance. Two criteria are used as performance measures. The first is that the systems have to operate at probability of bit error below a threshold, which is set to 10^{-9}. The second criterion is that the RZ eye profile has to be preserved at the receiver output to facilitate timing recovery. The first systems that we consider are single-span systems where the local dispersion is small. The single-span systems with moderate and large local dispersions, which require dispersion compensation, are also investigated. In addition, multiple-span systems employing in-line optical amplifiers as well as dispersion management to extend the total transmission distance are also considered. The results show that our proposed CWSW signal format outperforms the other considered signal

formats in many system configurations while the transmitter configuration of CWSW is simpler than the other approaches.

1.5 OUTLINE OF THIS WORK

The remaining chapters of this dissertation are organized as follows. The second chapter is dedicated to the discussions of various types of optical fibers and fiber configurations used in practical system implementations since this information is needed for realistic system simulations. This chapter begins with the properties of an optical fiber that affect signal propagation; they are dispersion and nonlinearity. The techniques used to mitigate the impairments caused by dispersion and nonlinearity are also discussed. It is then followed by the discussions of practical system configurations using different types of optical fibers.

Chapter 3 contains a comparison of previously proposed optical modulation formats. The advantages of the RZ signal format over the outdated NRZ signal format are discussed in the first section. In the second section of this chapter there is a discussion of nonlinear intrachannel impairments. The third section is dedicated to the effect of a dispersive nonlinear fiber on the propagation of an isolated Gaussian pulse with quadratic phase variation. We focus on how quadratic phase variation restores the output pulse width to its initial value at the fiber input. This is then followed by the practical implementation of quadratic phase variation by mean of synchronous phase modulation, which leads to the sinusoidal same phase modulation (SaPM) signal format. The other signal formats also discussed in this chapter are sinusoidal alternating phase modulation (APM), square-wave phase modulation (SWM), optical duobinary, and alternate mark inversion (AMI). Note that SaPM and APM are referred to as CRZ and nCRZ (novel CRZ), respectively, whereas SWM is equivalent to CS-RZ in the literature. For AMI, it is called DCS-RZ (Duobinary CS-RZ) or Modified duobinary in the literature. A conventional RZ signal format is also termed No PM. The purpose of renaming the modulation formats is to make them more understandable in terms of their phase characteristics in the time domain.

The discussion of our proposed CWSW signal format is provided in chapter 4. The details of CW to RZ pulse train conversion by square-wave phase modulation and

filtering are explained. Also presented in this chapter is the theoretical analysis of the PIE phenomenon. Twin displaced Gaussian pulses are selected as a mathematical model to describe this phenomenon. It is found that twin displaced Gaussian pulses well explain the PIE phenomenon.

Chapter 5 is dedicated to the discussion of the performance improvement obtained from synchronous phase modulation and filtering on the RZ signal format at the transmitter. The main objective is to understand the mechanisms that lead to performance improvement. Here we assume that the optical fiber is linear and lossless; hence, normalized SSF can be used. Three types of phase modulation are studied: sinusoidal alternating phase modulation (APM), sinusoidal same phase modulation (SaPM), and square-wave phase modulation (SWM). The performance improvement obtained from the CWSW signal format is also investigated. The system parameters that we consider are the modulation index of the phase modulation, normalized transmitter filter bandwidth, and normalized transmission distance. The results indicate that SWM and CWSW are effective in preserving the RZ eye profile due to spurious-pulse suppression whereas the pulse compression effect offered by SaPM does not prevent the growth of spurious pulses at all. For a wide range of parameters of interest, it is found that CWSW outperforms the other signal formats due to the PIE and capability of suppressing the growth of spurious pulses.

Then numerical simulations of practical system configurations are performed in Chapter 6. The bit rate that we consider is 40 Gb/s. Firstly numerical simulations for a system employing a dispersion-shifted fiber (DSF) with typical system parameters are conducted as a pilot case. The results suggest CWSW and AMI signal formats as the candidates for further in-depth studies. The parameters that we consider in the later numerical studies are the transmission distance, the transmitter filter bandwidth, and average transmitted power. For systems employing the DSF and optical preamplifiers, CWSW significantly surpasses the AMI signal format. The numerical simulations of single-link systems having moderate and large local dispersions with dispersion compensations are conducted, and it is found that CWSW and AMI are comparable in system performance, but CWSW has a bandwidth advantage. Multiple-span systems with

dispersion management are also investigated in order to understand how accumulated nonlinearity affects the system performance and optimum operating parameters.

Chapter 7 is the last chapter of this dissertation. The conclusions and principal contributions of this dissertation are provided in this chapter.

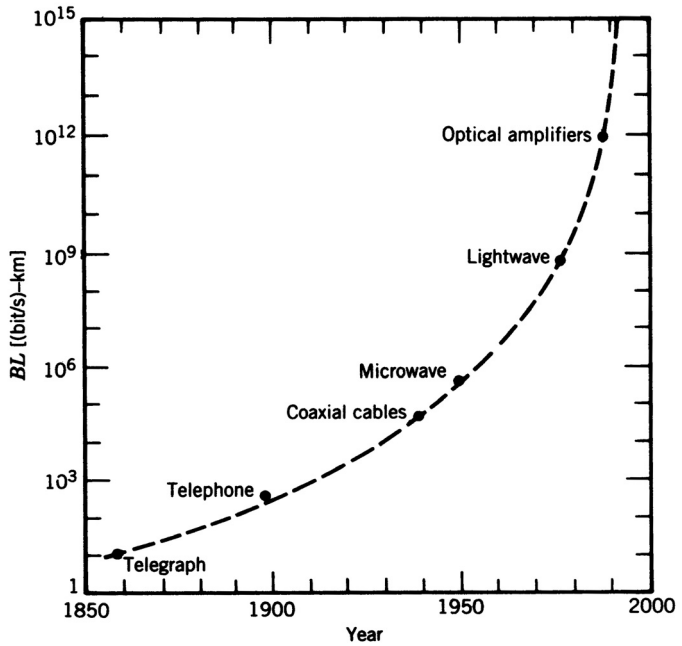


Fig. 1.1: Increase in bit rate-distance product during 1850-2000 [1].

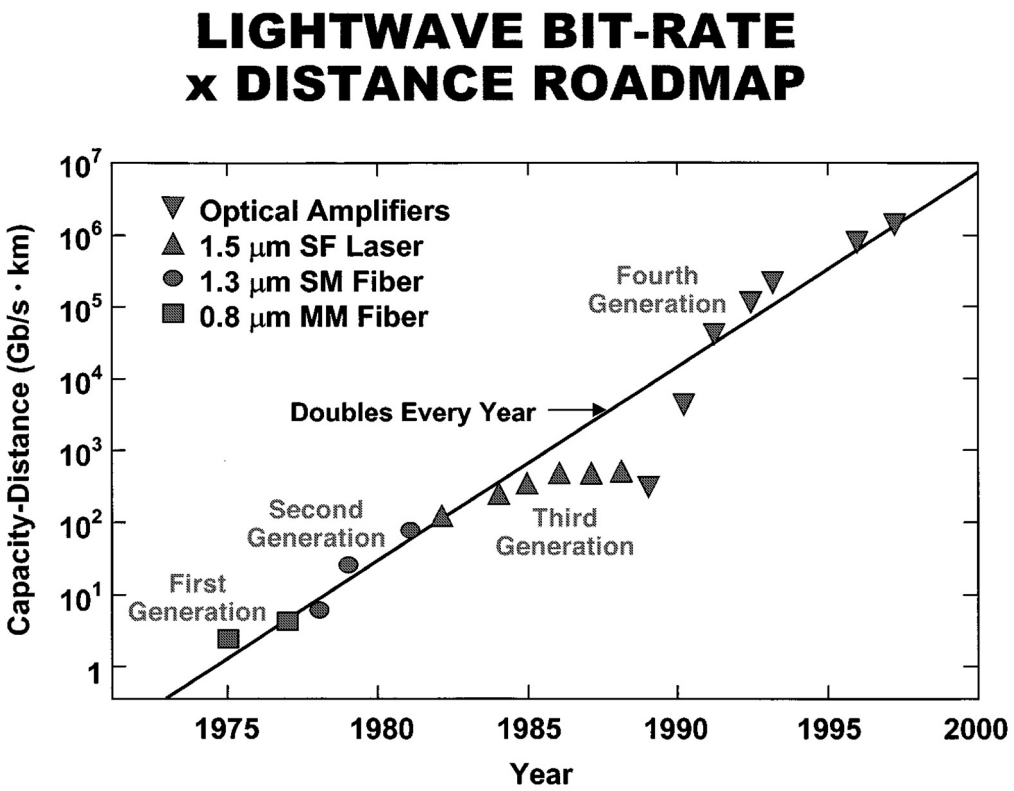


Fig. 1.2: Progress in bit rate-distance product of lightwave communication systems [4].

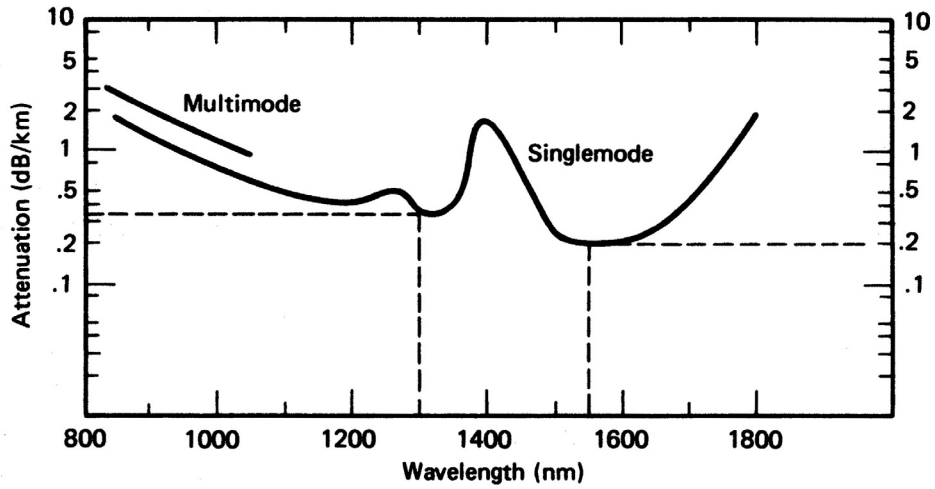


Fig. 1.3: Fiber attenuation as a function of wavelength for standard single-mode optical fiber [5].

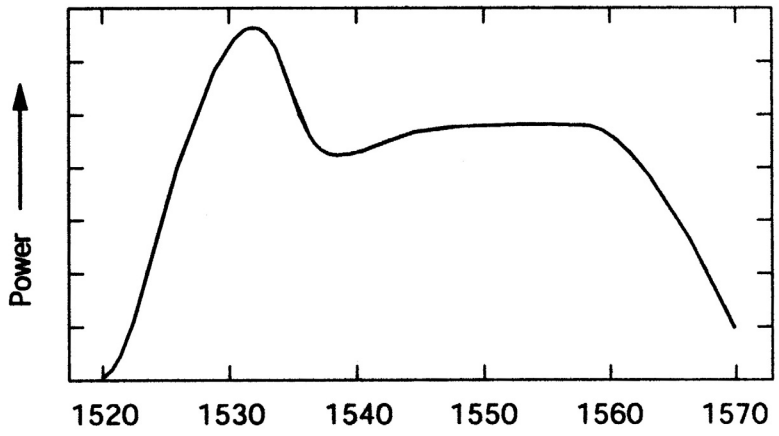


Fig. 1.4: Gain profile of the typical EDFA as a function of wavelength.

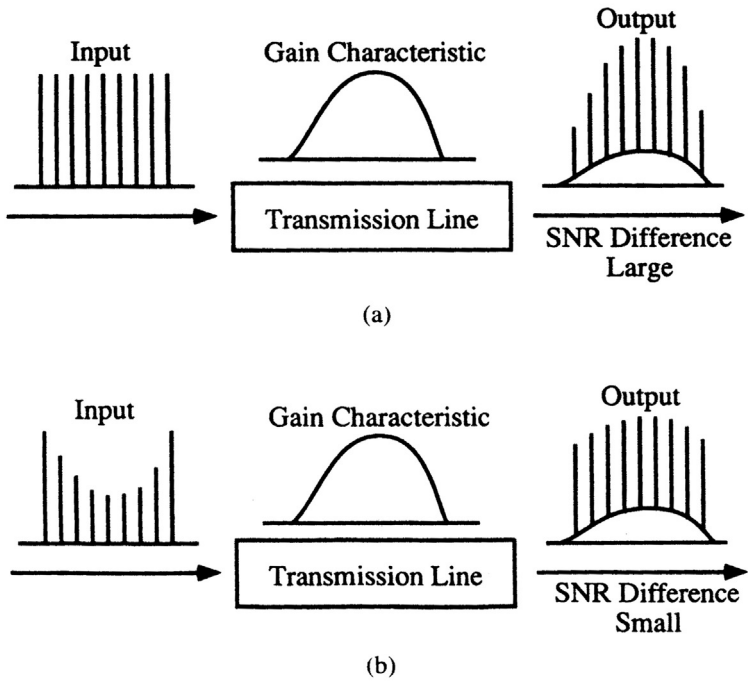
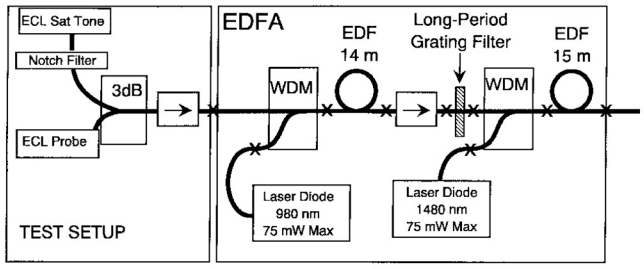
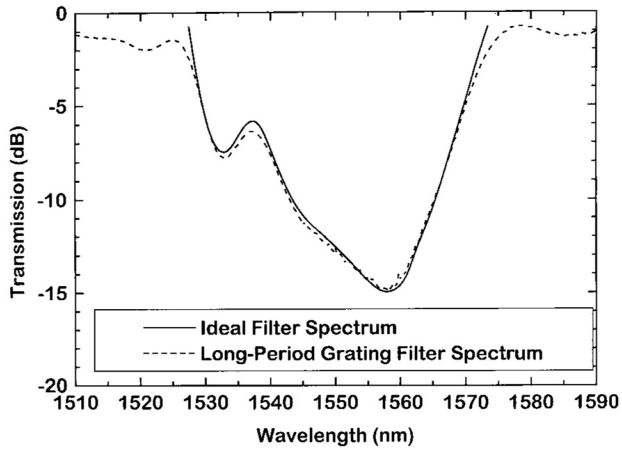


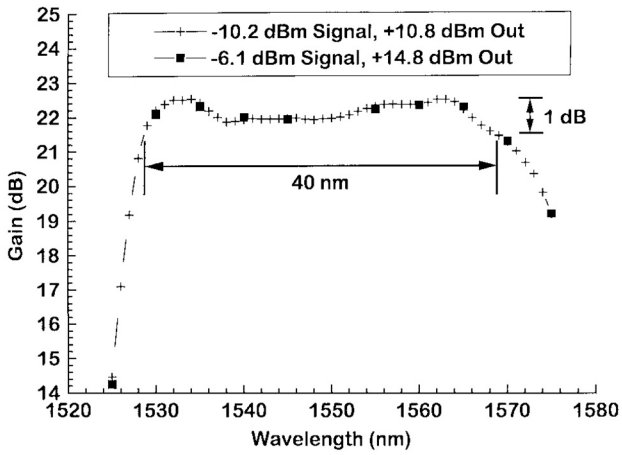
Fig 1.5: Pre-emphasis technique to equalize SNR among channels. (a) Conventional WDM system. (b) Pre-emphasis WDM system [28].



(a)



(b)



(c)

Fig. 1.6: (a) Schematic diagram of the gain-flattened EDFA using long-period grating filter. (b) Comparison between transmission characteristic of long-period grating filter and the calculated ideal transmission characteristic. (c) Gain spectrum of the EDFA incorporating the long-period grating filter. Stage 1 was pumped by 76 mW at 980 nm whereas Stage 2 was pumped by 34.5 mW and 74.5 mW at 1480 nm for two cases [31].

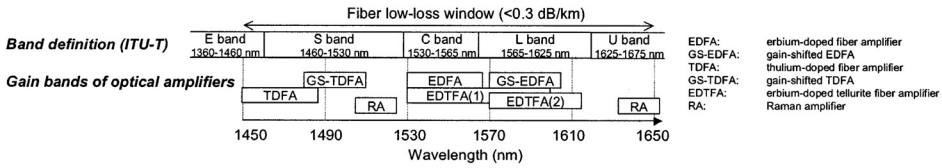


Fig. 1.7: ITU-T wavelength band definition and corresponding types of optical amplifiers [42].

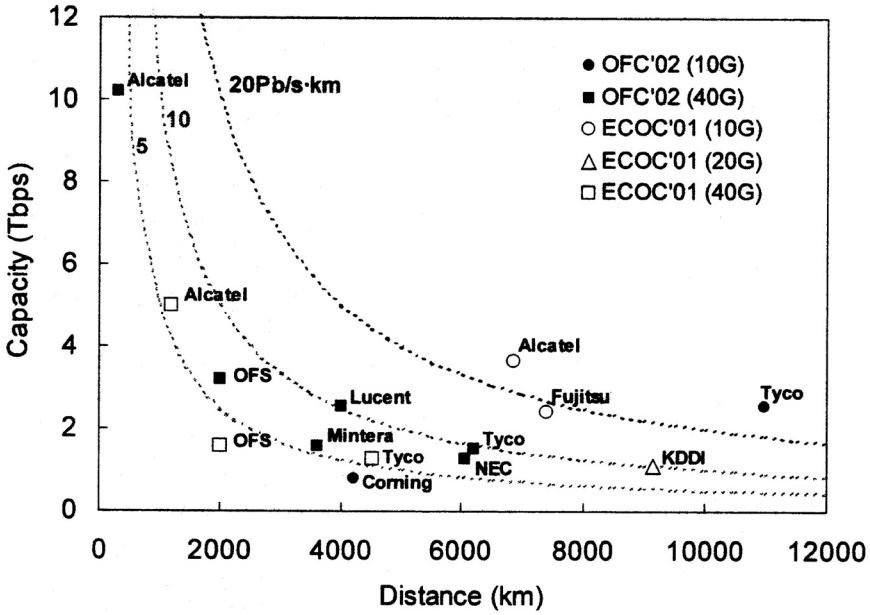


Fig. 1.8: Recent progress in transmission experiments [45].