Performance Analysis for an Optical CDMA System in Presence of Fiber Chromatic Dispersion

by

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APPROVAL CERTIFICATE

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(Afreen Azhari)

DEDICATED

To

My beloved Mother

And
My Most Respectable SIRE

Dr. A. H. Moinuddin Ahmed

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Contents:

List of Figures

List of Tables

List of Symbols

L	fiber length
D	fiber chromatic dispersion
c	speed of light
λ	wavelength
N_{th}	thermal noise
N_{sh}	shot noise
Q	complementary error function or co-error function
B_C	Chip rate
S_{SPK}	Phase shift keying modulate signal
$g(t)$	spreading signal in electrical domain
m	maximal length
γ	Fiber chromatic dispersion index
N	number of chip
B_K	baseband signal of the k-th user
T_b	bit period
Ai	spreading signal of i-th user in optical domain
P_T	transmitted power
P_R	received optical power
P_F	fiber loss
S_{OUT}	Fiber output before receiver
U	mean of signal
σ	Variance of interference
N_0	Variance of noise
R_L	Load resistance of the receiver
T	Receiver temperature
k	Boltzmann constant
K	number of simultaneous user
U_r	mean of signal without dispersion

List of Abbreviations

SNR	Signal-to-Noise Ratio
BER	Bit Error Rate
WDM	Wavelength Division Multiplexing
OTDM	Optical Time Division Multiplexing
FDM	Frequency Division Multiplexing
OCDMA	Optical Code Division Multiple Access
DS-CDMA	Direct Sequence Code Division Multiple Access
FH-CDMA	Frequency Hopping Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
FFH	Fast Frequency Hopping
WLAN	Wireless Local Area Networks
SIK	Sequence Inversion Keyed
SRS	Stimulated Raman Scattering
SBS	Stimulated Brillouin Scattering
FWM	Four-Wave Mixing
SPM	Self Phase Modulation
XPM	Cross Phase Modulation
FCD	Fiber Chromatic Dispersion
ASE	Amplifier's Spontaneous Emission
EDFA	Erbium-Doped Fiber Amplifier
LED	Light Emitting Diode
LASER	Light Amplification by Stimulated Emission of Radiation
APD	Avalanche Photodiode
ISI	Inter Symbol Interference
MAI	Multipath Access Interference
ACI	Adjacent Channel Interference

SMF	Single Mode Fiber
DSF	Dispersion Shifted Fiber
IM/DD	Intensity Modulation Direct Detection
LO	Local Oscillator
DCF	Dispersion Compensating Fiber
OOK	On-Off Keying
PSK	Phase Shift Keying
FSK	Frequency Shift Keying
ASK	Amplitude Shift Keying
MUX	Multiplexer
DeMUX	Demultiplexer
BPSK	Binary Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
OQPSK	Orthogonal Quadrature Phase Shift Keying
CPSK	Continuous Phase Shift Keying
DPFSK	Discontinuous Frequency Shift Keying
PPM	Pulse Position Modulation
ECC	Error-correcting codes
ET	Embedded transmission
SEC	Symmetric error correcting code
SSFBG	Superstructure Fiber Bragg Grating
PASS	Phased Aplitude-Sift Signaling
AWGN	Additive White Gaussian Noise
NRZ	Nonreturn to Zero
DSB-SC	Double-Sideband Suppressed Carrier
PN	Pseudo-Noise
OVSF	Orthogonal Variable Spreading Factor

Abstract

Optical code division multiple-access technique has recently received substantial attention in fiber optic communication for its asynchronous access, privacy and security. In this thesis, a detail analytical formulation is presented to study the impact of fiber chromatic dispersion induced on the bit error rate (BER) performance and eye diagram in terms of power penalty for direct sequence optical code division multiple access (DS-OCDMA) transmission link using an intensity modulated direct detection (IM/DD) sequence inverse keying (SIK) optical correlator receiver. The analysis is carried out considering the influence of fiber chromatic dispersion on the rectangular chips of the pseudo-noise (PN) sequence which results in interchip interference (ICI). 7 chip m-sequence and 32 chip Gold sequence are used in the simulation with number of simultaneous user as a parameter at a chip rate of 10Gchip/s. The simulation results reveal that with the increase in fiber chromatic dispersion, the system performance degrades and as a result higher power penalty is required, measured at a BER of 10^{-9}. The system can accumulate larger number of users at lower value of chromatic index. The system performance is also dependent on the type and length of sequence. The position and number of '1' in a same length chip sequence effect the power penalty.

Chapter 1

INTRODUCTION

1.1 Introduction to optical communication:

The last three decades have witnessed a spectacular progress in the field of optical fiber communications, lasers, optoelectronic devices and technology, in the development of semiconductor laser amplifiers and Erbium doped fiber amplifiers (EDFA) which enabled repeaterless transmission distance of more than 1000 km at a bit rate of 10Gbit/s. It has been established that, as compared to metal conductors/waveguides - size for size, optical fibers offer greater information capacity arising from a higher carrier frequency and lower material costs. Because of this reasons, during the last two decades there have been considerable advancements in the field of optical communication both in theory and practice [1].

1.2 Historical background of fiber optic communication:

The modern era of optical communication may be said to have originated with the invention of the laser in 1958 and early developments soon followed the realization of the first laser in 1960. After that K. C. Kao and Hockman experimented guided wave in which the laser beam was confined and was able to lay the foundation for the subject of fiber optic communication in 1966. But the attenuation was a minimum of 1000dB/km. By seeking ways to eliminate the absorbing impurities from the fiber, glass manufacturers led by Corning in the USA succeeded in reducing fiber attenuation to 2dB/km by 1975. In 1979, Japanese workers had obtained minimum attenuation of .2dB/km. This involved longer wavelengths (1.3 and 1.55μm). By the mid 1980s, fiber having a guaranteed attenuation of less than .4dB/km at 1.3μm and less than .25dB/km at

1.55μm was commercially available that carry telephone, cable TV and other types of telecommunication traffics.

1.3 Advantages of optical fiber communication:

In addition to the advantages of having extra information bandwidth, using light as a carrier signal, the optical fiber communication systems have several other advantages over the conventional systems.

a) Extra advantages of having low weight and small in size.
b) The immunity to ambient electrical noise, ringing echoes or electromagnetic interference.
c) No hazards of short circuits as in metal wires.
d) No problems when used in explosive environments.
e) Immunity to adverse temperature and moisture conditions.
f) Lower cost of cables per unit length compared to that of metal counter-part.
g) No need for additional equipment to protect against grounding and voltage problems.
h) Very nominal shipping, handling and installation costs.

Because of these advantages fiber optic communication is being currently utilized in telephone such as loops, trunks, terminals and exchanges, etc., computers, cable television, space vehicles, avionics, ships, submarine cable and security and dark systems, electronic instrumentation systems, medical systems, satellite ground stations and industrial automation and process control. The coming development of integrated optic technology is hoped to play a bigger part in influencing further departures from existing concepts of electronic systems for communication, control and instrumentation.

1.4 Basic concept of optical communication system:

The schematic diagram of a general communication system is shown in Fig. 1.1 In this case the information source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of lightwave carrier. The optical source, which provides the electrical-optical conversion may be either a semiconductor laser or a light emitting diode (LED). The transmission medium consists of an optical fiber and the receiver consists of an optical detector (p-i-n or avalanche) which drives a further electrical stage and hence provides demodulation of the optical carrier.

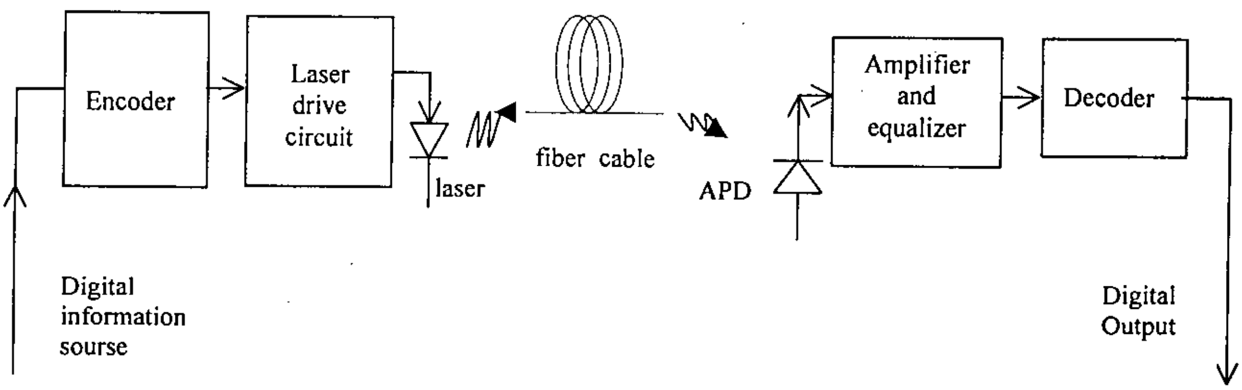

Fig. 1.1 Block diagram of a general optical system

1.5 Detection schemes:

In optical communication system, there are two important detection schemes employed. These are:

a. Coherent Detection

b. Intensity Modulation Direct Detection (IM/DD)

Coherent Detection:

In coherent detection the received optical signal is combined with the light output from a local oscillator (LO) laser and the mixed optical signal is converted to an intermediate frequency (heterodyne) or directly to baseband by homodyne. In this system information can be impressed on the optical carrier in three ways 1) phase shift keying (PSK) 2) frequency shift Keying (FSK) 3) Amplitude shift keying (ASK). Depending on the specific application, various modulation and demodulation formats similar to those of traditional radio frequency communication are also employed in coherent lightwave transmission. These include binary PSK (BPSK), quadrature PSK (QPSK), orthogonal QPSK (OQPSK), continuous phase (CPSK), discontinuous phase FSK (DPFSK), Pulse position modulation (PPM), etc. Each of the modulation scheme and combinations thereof, with homodyne, heterodyne or diversity receivers has it's own merits and demerits and none has emerged as absolutely preferable.

Intensity Modulation Direct Detection (IM/DD):
In the direct detection scheme, the intensity of received optical field is directly converted to a current by a photodetector. The sensitivity of an ideal direct detection receiver is determined by the statistical distribution of the detected photons. As no electrical modulation or demodulation is required in this technique, so it is both inexpensive and easy to implement.

1.6 Advanced multiplexing strategies in IM/DD technique:

In order to maximize the information transfer over an optical fiber communication link it is usual to multiplex several signals on to a single fiber. The different multiplexing techniques employed with IM/DD optical fiber system are optical time division multiplexing (OTDM), wavelength division multiplexing (WDM), or a hybrid approach to achieve tera bit per second channel capacity. Now a days, interest is beginning to grow in investigating alternative multiplexing scheme such as optical code division multiple access (OCDMA) that can further enhance the functionality of optical networks.

WDM: WDM involves the transmission of a number of different peak wavelength optical signals in parallel on a single optical fiber (Fig. 1.2). Although in spectral terms optical WDM is analogous to electrical frequency division multiplexing, it has the distinction that each WDM channel effectively has access to the entire intensity modulation fiber bandwidth, which with current technology is of the order of several gigahertz.

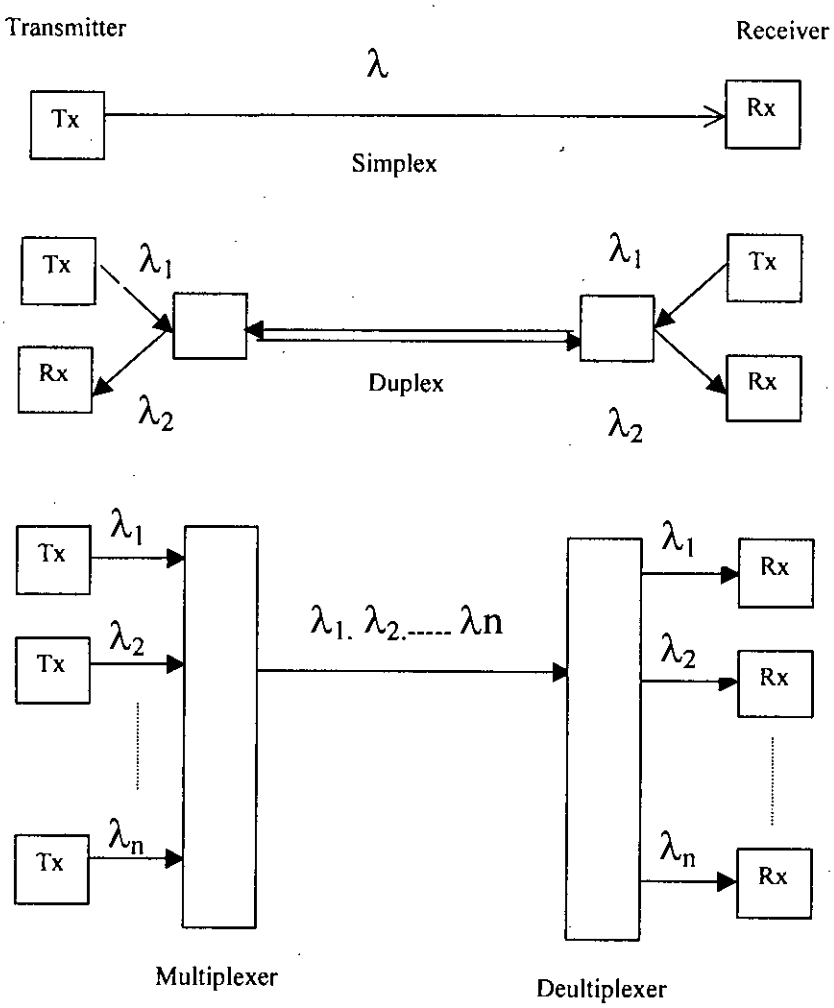

Fig. 1.2 Optical fiber system illustrating wavelength division multiplexing

OTDM: The principle of OTDM technique is to extend time division multiplexing by optically combining a number of lower speed electronic baseband digital channels. (Fig.1.3).

OCDMA: In recent years OCDMA systems have experienced increasing research attention in the last decade because they offer several attractive features such as asynchronous access, privacy and security in transmission, ability to support variable bit rate and busy traffic and scalability of the network. Here all users can

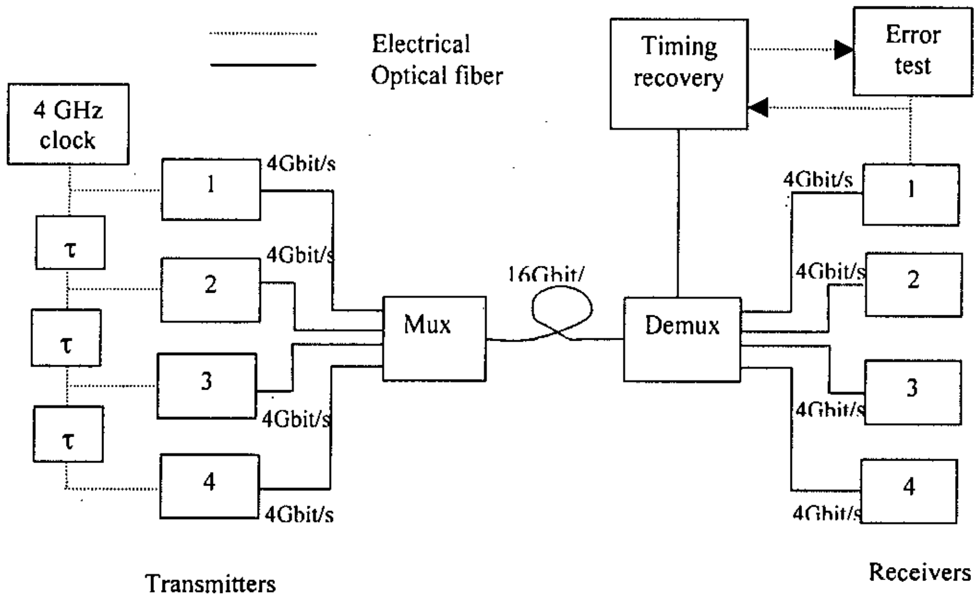

Fig.1.3 Four channel OTDM fiber system

asynchronously access the network in a very flexible manner without any timing devices and optical electrical conversion. It is convenient to exploit very broad bandwidth of optical fiber and implement the very large speed communication system in OCDMA. It permits a large number of separate users to share the same extended transmission optical bandwidth but to be individually addressable through the allocation of specific address code signature sequence with good correlation properties. The encoding can be performed either in the time domain [direct sequence (DS-CDMA)] or frequency domain [frequency hopping (FH-CDMA)].

1.7 Limitations of optical fiber communication system:

Though optical communication system is more advantageous, there are some limitations of optical fiber communication systems. These are:

(i) Stimulated Raman Scattering (SRS)

(ii) Stimulated Brillouin Scattering(SBS)

(iii) Cross-phase modulation (XPM)

(iv) Self Phase Modulation (SPM)

(v) Four Wave Mixing. (FWM)

(vi) Fiber Chromatic Dispersion (FCD)

(vii) Laser Phase Noise

(viii) Optical Amplifier's spontaneous emission (ASE) noise

Stimulated Raman Scattering (SRS): Stimulated Raman scattering is an interaction between light and vibrations of silica molecules and causes attenuation of short wavelength channels in wavelength multiplexed systems. [2-3]

Stimulated Brillouin Scattering (SBS): Simulated Brillouin Scattering is an interaction between light and sound waves in fiber and causes frequency conversion and reversal of the propagation direction of light. [4-5].

Cross-phase modulation (XPM): Cross-phase modulation is an interaction, via the nonlinear refractive index between the intensity of one lightwave and the optical phase of the other lightwaves [6].

Four Wave Mixing (FWM): Four wave mixing is analogous to third order intermodulation distortion whereby two or more optical waves at different wavelengths mix to produce new waves at other wavelengths. Stimulated Brillouin Scattering (SBS) and FWM process are likely to impose severe restriction transmitter power in FDM system [7-8].

Fiber Chromatic Dispersion: The impulses of various wavelength travel at different speeds through the optical fiber and at the output impulses get widening. Thus widening of the impulses depends on the spectral width of the source. This effect known as chromatic dispersion (Fig. 1.4). [9].

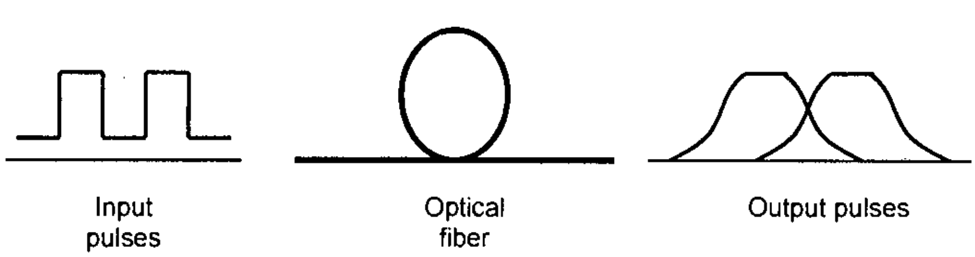

Fig.1.4 ISI due to fiber Chromatic dispersion

If the bit rate increases i.e. time slot decreases the impulses will overlap and no longer be distinguished from each other generating intersymbol interference (ISI) effect, thus limiting transmission bit rate. The three main major types of dispersion are: (Fig.1.5)

(i) Material Dispersion

(ii) Waveguide Dispersion

(iii) Profile Dispersion.

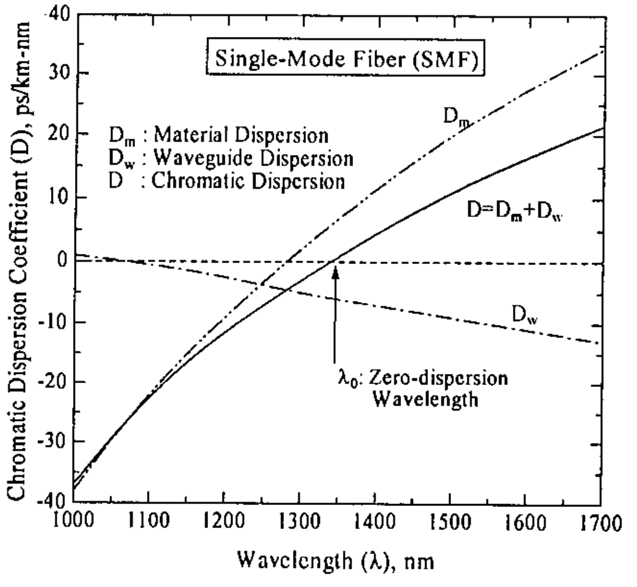

Fig. 1.5 Chromatic dispersion characteristics of standard SMF

Martial Dispersion, D_m: It occurs when the phase velocity of a plane wave propagating in the dielectric medium varies nonlinearly with wavelength and a material is said to exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero.

Waveguide Dispersion, D_w: It results from the variation of group velocity with wavelength for a particular mode and causes intramodal dispersion as the modal propagation constant is a function of optical fiber dimension relative to wavelength.

Profile Dispersion: It originates from the refractive index profile but it's contribution is insignificant.

Total Dispersion, D; The contribution of different dispersion effects i.e. D_m and D_w, to a first approximation can be added algebraically. D_w has opposite sign compared to D_m .

If ϒ represents the fiber chromatic dispersion Index, then it can be expressed as

$$\Upsilon = \text{Chromatic dispersion index of the fiber} = \frac{\lambda^2}{\pi c} D {b_c}^2 L$$

Where,

λ = optical wavelength corresponding to the carrier frequency.

D = Fiber chromatic dispersion index parameter

bc = chip rate

L = fiber length.

Here, we find that the amount of dispersion is directly proportional to the fiber length. Chromatic dispersion results in limiting the fiber transmission capability, due to variation in propagation time as a function of wavelength and hence a reduction of transmission system performance.

1.8 Previous works on optical code division multiple access (OCDMA);

Optical code division multiple access (OCDMA) systems have experienced increasing research attention in the last decade. There are two main types of techniques used to spectrally code and spread a data signal; these are the so-called direct-sequence (DS) CDMA, and frequency-hopping (FH) CDMA. However it is also possible to use hybrid approaches that combine the two techniques. Most of the research on optical CDMA has concentrated on the intensity modulation and direct detection signaling for example on-off keying (OOK) [11], [12] and pulse position modulation (PPM) [13], [14]. PPM is preferable to OOK because the pulse position multiplicity reduces the effect of multiple access interference (MAI) in addition to good power efficiency of PPM against OOK. [13]. However the prime disadvantages of using PPM in optical CDMA is the decrease in transmission rate relative to the speeds available in the laser and it worsens as the signature sequence length becomes long. A number of optical orthogonal code (OOC) have been proposed [14], [15], [16] for various OCDMA technology. To support data-format-independence, data rate independence as well as time transparent transmission in multimedia applications, novel classes of OOCs are required. Conventional OOC families are designed to support constant bit rate applications [14], [17-19]. When such codes are used to support the variable-bit-rate or multiple bit rate multimedia applications, their predetermined cross-correlation is valid under fixed weight and code length. Due to unequal and changeable codeword length, can be violated. To avoid such situations, several novel classes of OOCs have been recently proposed [20-21]. A novel constant-length variable-weight class of OCC is proposed in [22]. These are suitable for spectral amplitude coding, fast frequency hopping and time spreading encoding in multimedia environment.

A unipolar-bipolar correlation allows conventional bipolar signature sequences to be used in a sequence inversion keyed (SIK) direct sequence (DS) code division multiple access (CDMA). For the same bandwidth expansion factor conventional bipolar signature sequences exhibit larger set sizes thereby supporting more simultaneous users and lower (MAI) than either prime codes [23] or optical orthogonal codes [10]. The bit error rate performance of an all-optical parallel delay line unipolar-bipolar correlator has been reported in [24]. An optically switched unipolar-bipolar correlator receiver has been demonstrated in [25] which is assessed as a function of the incident optical power for non-coherent transmission and direct detection with the number of simultaneous user as a parameter.

Phase encoded OCDMA has attracted the attention of experts on optical communication where the carrier is phase modulated by the digital data sequence and the code sequence. Several experiments on phase encoded OCDMA were reported recently. An asynchronous phase coded spread spectrum system has been investigated in [26], concentrating on communication performance rather than on acquisition and tracking performance. The need for considering the impact of fiber channel in an asynchronous phase encoded OCDMA has been demonstrated [27], where phase encoded optical signal is analyzed in the view of stationary random processes.

Another approach to produce better channel BER performance is the use of error-correcting codes (ECCs) [28], [29]. The channel coding involves either decreasing the symbol duration or decreasing the information rate. To apply ECCs into the optical CDMA effectively, the embedded modulation scheme is investigated [30], [14]. An embedded transmission scheme which is the modified version of the embedded transmission (ET) scheme has been described in [14], The effectiveness of ET transmission with symmetric error correcting code (SEC) scheme has been applied in [31] using PPM signaling. Turbo code is one of the interesting research topics, because it offers its substantial gain over uncoded systems and its reasonable decoding complexity as shown in [32], [33].

Recently a number of DS-CDMA systems based upon fiber Bragg grating encoding–decoding devices has been demonstrated [34]. These particular experiments showed the suitability of using superstructure fiber Bragg grating (SSFBG) technology for the generation, recognition, and recoding of phase-encoded optical code sequences containing as many as 63 chips at chip rates as high as 160 Gchip/s. Longer code sequences and higher chip rates should also be possible. An SSFBG can be defined as a standard fiber grating, i.e., a grating with a rapidly varying refractive index modulation of uniform amplitude and pitch, onto which a slowly varying refractive index modulation has been applied along its length. SSFBGs can, thus, be designed and fabricated with a wide range of complex tailored impulse-response functions with precise amplitude and phase characteristics. Such SSFBGs should find application within a variety of optical-pulse processing systems [35], [36], including use within both DS-OCDMA code generation and recognition devices, and for which precise control of the amplitude and phase of the temporal pulse profile is essential.

Fiber dispersion causes spreading of an optical pulse, which in turn degrade system performance due to increased intersymbol interference and reduced received optical peak power [37]. Chromatic dispersion limitations for coherent systems were studied by considering the effect of PM to AM conversion for a sinusoidally phase modulated source [38], [39]. The dispersion penalty associated with this effect for random data sequences was not evaluated because of the complexity involved in solving the problem analytically. Earlier dispersion penalty calculations, applicable to microwave radio systems [40] or direct detection lightwave systems with Gaussian pulse shape [41], [42] have been used recently to estimate chromatic dispersion penalties in coherent and OOK systems, use a variety of simplifying approximation for modeling the single mode fiber and for dealing with differences in receiver demodulation techniques. An appropriate amplitude and phase response and difference in receiver demodulation techniques are taken into account for analyzing fiber chromatic dispersion effect in coherent lightwave system [43]. Here the theoretical performance limitations due to fiber chromatic dispersion on coherent ASK and DPSK system has been reported. The experimental result of chromatic dispersion limitations on direct detection FSK and DPSK system was also reported in [44]. A novel family of optical line codes have been presented in [45] to counter act the effect of a dispersive fiber. The performance of this first code in the family, referred to as order 1 code, is analytically evaluated and is better, in certain cases, compared to that of the duobinary and phased amplitude-shift signaling (PASS) codes proposed in [46].

Recently the performance of an asynchronous phase encoding OCDMA considering fiber chromatic dispersion has been reported in [37]. Bit error rate analysis of this system has been performed in the case of both ordinary single mode optical fiber and dispersion shifted fiber. The numerical results demonstrate that even though the system performance improves due the smaller width of initial Gaussian optical pulse, the effect from disprsion is higher.

Anyway in DS-OCDMA using direct detection intensity modulation (DD-IM) scheme, the impact of fiber chromatic dispersion on system performance has been neglected in almost all works as they have considered each chip sequence as rectangular shapes rather than the Guassian fiber output, arising from fiber chromatic dispersion.

1.9 The objective of the thesis:

The main objectives of this thesis work are:

(1) To carry out an analysis of an direct sequence optical code division multiple access (DS-OCDMA) transmission link in the presence of fiber chromatic dispersion, using an intensity modulated direct detection (IM/DD) sequence inverse keying (SIK) optical correlator receiver .

(2) To evaluate the bit error rate (BER) performance of the receiver under the effect of intersymbol interference (ISI) due to fiber chromatic dispersion for the different values of chromatic dispersion index and different types of code sequence at a given chip rate of 10Gchip/s.

(3) To determine the bit error rate (BER) performance of the receiver for number of simultaneous users that causes the multiple access interference (MAI) for different types of code sequence and fiber chromatic dispersion index, at a given chip rate of 10Gchip/s.

(4) To find out, for a given bit error rate, the amount of power penalty suffered by the system on the bit error rate performance due to fiber chromatic dispersion index and multiuser interference, separately, for different type of code sequence, at a chip rate of 10Gchip/sec.

(5) Finally, to find optimum system parameters, viz. type and length of code sequence, number of simultaneous users, reliable system performance at a given chip rate, bit error rate and fiber dispersion index.

1.10 Brief introduction to this thesis:

In chapter 1, a brief introduction and historical background of optical communication systems are discussed. The main features of optical communication systems are presented. Advanced multiplexing strategies, limitation of optical fiber communication and a review of recent works in the related field are also presented.

In chapter 2, an introduction to electrical code division multiple access (CDMA), different types of code sequences for CDMA, Optical code division multiple access (OCDMA) system model, using direct detection asynchronous SIK correlator and a theoretical analysis are presented for a direct sequence IM/DD, Optical CDMA transmission link in the presence of fiber chromatic dispersion, thermal noise and photodetector shot noise.

Chapter 3 provides the performance results of direct sequence optical CDMA transmission link SIK correlator for different sets of values of fiber chromatic dispersion index, number of simultaneous users and for different types and length of code sequence at a chip rate of 10Gchip/sec.

A brief conclusion and suggestions for future work are presented in chapter 4.

CHAPTER 2

Analysis of Optical Code Division Multiple Access (OCDMA) Transmission System

2.1 Overview of spread spectrum:

Spread spectrum is a technique where a modulated signal is further modulated (spreaded) in such a way so as to generate an expanded bandwidth wideband signal that does not significantly interfere with other signals. Bandwidth expansion achieved by a second modulation is independent of the information message. For this reason, this expansion does not combat additive white Gaussian noise (AWGN), as does wideband frequency modulation (FM).

The term spread spectrum has been used in a wide variety of military and commercial communication systems. In spread spectrum, systems each information signal requires significantly more radio frequency (RF) bandwidth than a conventional modulated signal would require. The expanded bandwidth provides certain desirable features and characteristics that could otherwise be difficult to obtain.

Application and potential advantages of spread spectrum system include the following:

- Improved interference rejection
- Code division multiplexing for code division multiple access (CDMA) application.
- Low density power spectra for signal hiding
- High resolution ranging
- Secured communication

- Lower cost of implementation using readily available IC (Integrated Circuit) components.

2.2 Electrical CDMA:

In electrical domain, Code division multiple access (CDMA) is a kind of spread spectrum (SS) technique. Spread Spectrums have been classified by their architecture and modulation concepts [48]. The most commonly employed SS modulation techniques in electrical domain are:

- Direst sequence spread spectrum (DS-SS), including CDMA
- Frequency hopping (FH), including slow frequency hopping (SFH) and fast frequency hopping (FFH) system
- Carrier sense multiple access (CSMA) spread spectrum
- Time hopping
- Hybrid Spread Spectrum Method

In mobile radio systems and wireless local area networks (WLAN), direct sequence, frequency-hopped CDMA and CSMA methods have been extensively used.

Fundamental concepts of spread spectrum system:

A conceptual diagram of direct-sequence spread spectrum system is given in Fig. 2.1(a,b). The digital binary baseband information, d(t), also known as nonreturn to zero(NRZ) data, having a source bit rate of $f_b=1/T_b$, is phase shift key (PSK) modulated in the first modulator. To illustrate the fundamental concept, a simple unfiltered, constant envelope (hard limiter) binary PSK modulation has been assumed. The modulated binary PSK signal $S_{PSK}(t)$ is given by:

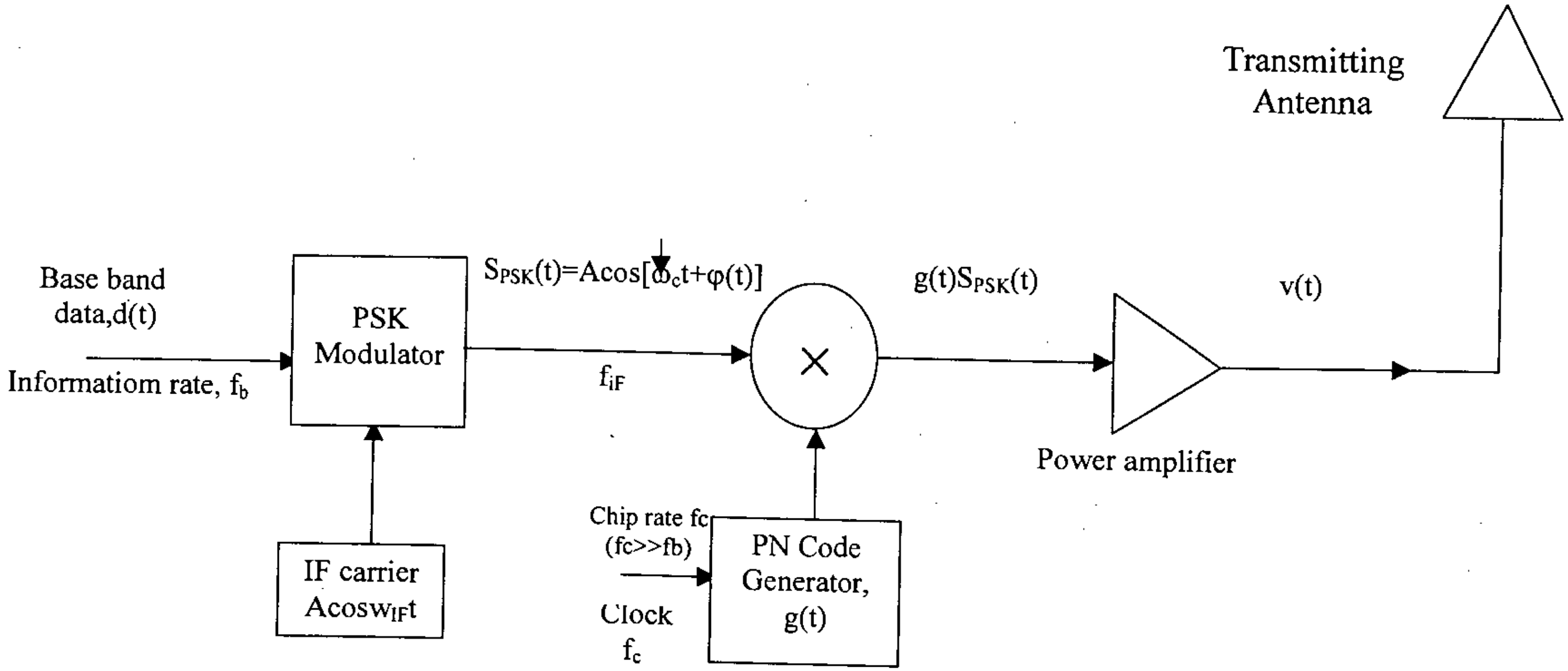

Fig 2.1a Transmitter Block Diagram of a Direct Sequence Spread Spectrum System

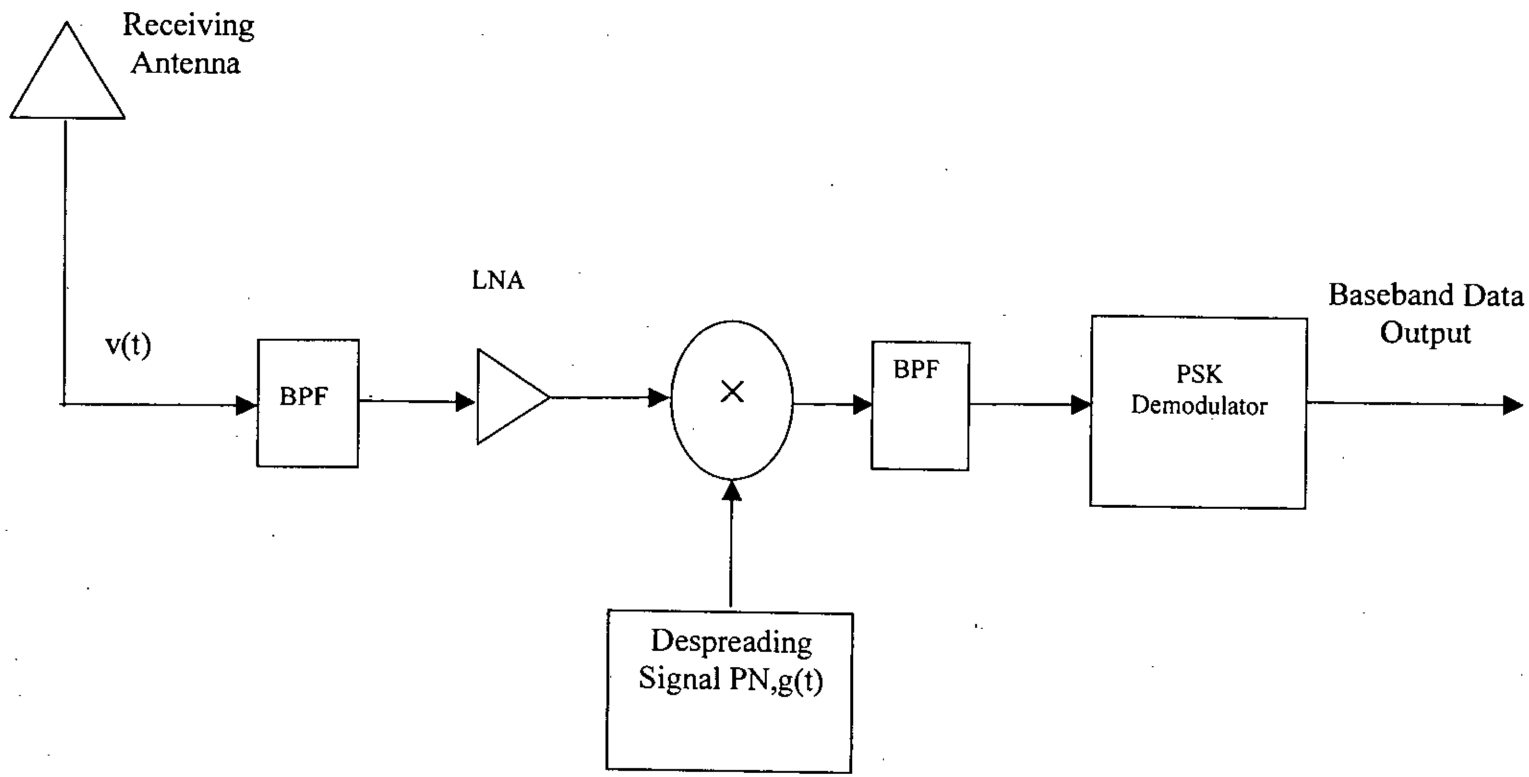

Fig 2.1b Receiver Block Diagram of a Direct Sequence Spread Spectrum System

$$S_{PSK}(t)=\sqrt{2P_S}.d(t).\cos w_{if}t \qquad (2.1)$$

where d(t) is an unfiltered binary signal having two states +1 or -1,
w_{if} is the carrier frequency, and P_s is the corresponding carrier power. The spreading signal g(t) is a pseudonoise (PN) signal having a chip rate of $f_c=1/T_c$. The Binary PSK(BPSK) modulated DS-SS is given by

$$v(t)=g(t)S_{PSK}(t)=\sqrt{2P_s}\,g(t)d(t)\cos\omega_o(t) \qquad (2.2)$$

The intermediate frequency (IF) signal is upconverted by an RF synthesizer to the desired transmission frequency, ω_{rF}. In this notation, ω_o correspond to the frequency ω_{iF} or to the upconverted RF, ω_{rF}.

It is assumed that in a wireless mobile system, within the same cell there are several simultaneous users. Each user is assigned the same RF carrier frequency f_{rf}, and occupies the same Rf bandwidth, $B_{rf.}$ The spread spectrum generation process in a multiple access system application involves two fundamental steps: modulation and spreading (or second modulation by a PN sequence). The second modulation is assumed to be an ideal, multiplication $g_i(t)s_i(t)$, (Fig2.1.a,b). Ideal multiplication is equivalent to double-sideband suppressed carrier (DSB-SC) amplitude modulation (AM). The position of the first and second modulators can be interchanged without any impact on the theoretical system performance.

The spread spectrum signal $g_i(t)s_i(t)$ is upconverted to RF frequency. The upconversion (U/C) and downconversion (D/C) processes are practical requirements in most system applications; however this is not a fundamental step and hence has not been shown in Fig(2.1.a). It is assumed that IF $g_i(t)s_i(t)$ ie. $v_i(t)$ signal is transmitted and received. That is the upconversion and downconversion is bypassed. Thus the $g_i(t)s_i(t)$ spread spectrum signal is transmitted and at the receiver it is combined with other M independent spread spectrum signals that use the same RF band. The combined received signal is given by

$$r(t) = \sum_{i=1}^{M} g_i(t)s_i(t) + I(t) + n(t) \tag{2.3}$$

where M is the number of simultaneous users, $g_i(t)$ is the spreading function or PN code of the "i" -th transmitter/receiver pair, $s_i(t)$ is the modulated signal, I(t) is interference (deliberate or self noise) and n(t) is AWGN.

At the receiver the intended user will have a synchronized $g_i(t)$ despreading function which is the same PN sequence as that of the corresponding transmitter. The despread signal is PSK demodulated. Other modulation method such as MSK, GMSK, GFSK, FM, FBPSK or FPQSK have also been implemented in spread spectrum systems.

If the chosen set of PN spreading waveforms are not cross-correlated, then after despreading only the desired modulated waveform $s_i(t)$ remains. All other waveforms are not correlated and are effectively spread over a much wider bandwidth than that of the final demodulator bandwidth.

Pseudo-Noise Sequences:

The major tasks of the pseudonoise (PN) sequences used in wireless digital or personal communication DS-CDMA systems are the following.

1. Spreading the bandwidth of the modulated signal to the larger transmission bandwidth;
2. Distinguishing between the different user signals utilizing the same transmission bandwidth in a multiple access scheme;

To meet these tasks, the sequences need special correlation properties.

In the known wireless communication system, the spreading signals are binary digital PN codes. Autocorrelation and crosscorrelation of code sequences are obtained by computing the number of agreements (A) minus the number of disagreements (D), when the codes are compared bit by bit for every discrete shift τ in the field of interest.(Fig 2.2a,b)

To solve the spreading task and to occupy the transmission band equally, the power spectrum of a single sequence should be like white Gaussian noise. Such a sequence could be generated by the scheme shown in Fig. 2.3, where a noiselike digital data pattern has been I obtained by "sample and hold". The sampling frequency corresponds to the chip rate $f_c=1/T_c$. The autocorrelation function of the signal is shown in Fig 2.2.b. The single sharp peak in the autocorrelation function at the time shift $\tau=0$ is a desired property and supports an easy receiver synchronization. If the sequence is repeated in a periodic manner after N chips, a pseudo-noise (PN) or pseudo-random type of sequence is achieved. For this PN sequences a periodic autocorrelation function is obtained.

The second and more difficult task of the PN sequence for a multiuser CDMA system is to distinguish between the signals of the different users utilizing the same transmission bandwidth. The PN code is the key of each user to his or her intended signals in the receiver. For this reason the complete set of PN sequences has to be chosen with a with a small cross correlation between the several sequences. This keeps the adjacent channel interference (ACI) small. Theoretically a zero crosscorrelation is maintained by every set of orthogonal spreading signal (such as the Fourier series and Walsh function). However in practical wireless systems one has to design for easy, coherent generation of the PN sequence, on both the transmitter and the receiver sides.

The best-known, best-described PN sequences are maximal- length sequences (*m-sequences*). They are suitable for single user spread spectrum systems and widely used in military applications. Because of the cross correlation demands, Gold sequences, Kasami-sequences, or Walsh-sequences are more interesting for cellular or personal CDMA systems. Sometimes they are combined with m-sequences.

CDMA Multiple-Access:

The advantage of CDMA for personal communication services is its ability to accommodate many users on the same frequency at the same time. As we mentioned earlier, a specific code is assigned to each user and only that code can demodulate the transmitted signal.

There are two ways of separating users in CDMA:

- Orthogonal Multiple Access
- Non-orthogonal Multiple Access or Asynchronous CDMA

Orthogonal Multiple Access

Each user is assigned one or many orthogonal waveform derived from an orthogonal code. Since the waveforms are orthogonal, users with different codes do not interfere with each other. Orthogonal-CDMA or O-CDMA requires synchronization among the users, since the waveforms are orthogonal only, if they are aligned in time.

Orthogonal Codes

An important set of orthogonal code is the *Walsh* set. Walsh functions are generated using an iterative process of constructing a Hadamard matrix starting with $H_1 = [0]$. The Hadamard matrix is built by:

$$H_{2n} = \begin{pmatrix} H_n & H_n \\ H_n & \overline{H_n} \end{pmatrix}$$

For example, here are the Walsh-Hadamard codes of length 2 and 4 respectively:

$$H_2 = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} H_4 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

From the corresponding matrix, the Walsh-Hadamard codewords are given by the rows. Usually the binary data is mapped to polar form so that real numbers arithmetic can be used when computing the correlations. So 0's are mapped to 1's and 1's are mapped to -1.

Walsh-Hadamard codes are important because they form the basis for orthogonal codes with different spreading factors. This property becomes useful when we want signals with different Spreading Factors to share the same frequency channel. The codes that possesses this property are called Orthogonal Variable Spreading Factor (OVSF) codes. To construct such codes, it is better to use a different approach than matrix manipulation. Using a tree structure allows better visualization of the relation between different code length and orthogonality between them.

However, the auto-correlation function of Walsh-Hadamard codewords does not have good characteristics. It can have more than one peak and therefore, it is not possible for the receiver to detect the beginning of the codeword without an external synchronization scheme. The cross-correlation can also be non zero for a number of time shifts and un-synchronized users can interfere with each other. This is why Walsh-Hadamard codes can only be used in synchronous CDMA.

Walsh-Hadamard codes do not have the best spreading behavior. They do not spread data as well as PN sequences does, because their power spectral density is concentrated in a small number of discrete frequencies.

Non-Orthogonal Multiple access:

The concept behind this is to give up orthogonality among users and reduce the interference by using spread spectrum techniques. PN sequences are used to spread the spectrum. The family of PN sequences, called *Gold* sequences are in particular popular for non-orthogonal CDMA. Gold sequences have only three cross-correlation peaks, which tend to get less importance as the length of the code increases. They also have a single auto-correlation peak at zero, just like ordinary PN sequences.

m-Sequence:

In this section maximal length linear code or maximal length shift register sequences are described, since these codes are still of importance in digital communications and in spread spectrum and ranging systems. An illustrative, widely used hardware implementation of a PN sequence generator and corresponding correlator and matched data filter register has been shown in Fig 2.4. The generator contains type D flip flops and is connected so that each data input except D_O is the Q output of the preceding flip flop. Not all Q flip flop outputs need be connected to the parity generator (indicated by the dashed lines). The number of flip flops L and the selection of which flip flop outputs are connected to the parity generator determine the length and the characteristics of the generated PN sequence. The parity generator provides an output logic 0, when an even number of inputs are at logic 0 and generates logic 1 output when an odd number of inputs are at logic 1 state.

Sequence length:

For maximal length linear codes, it is always possible to find a set of connections from flip-flop outputs to the parity generator that will yield a maximal length sequence of

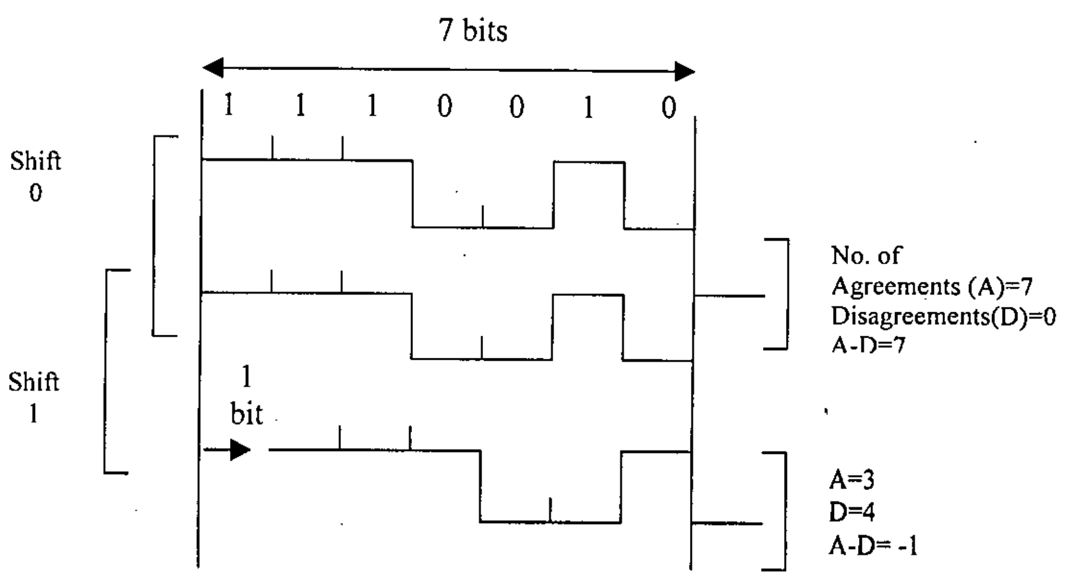

Fig 2.2(a) Computation of
Autocorrelation and Cross Correlation

$$L = 2^N - 1 \tag{2.4}$$

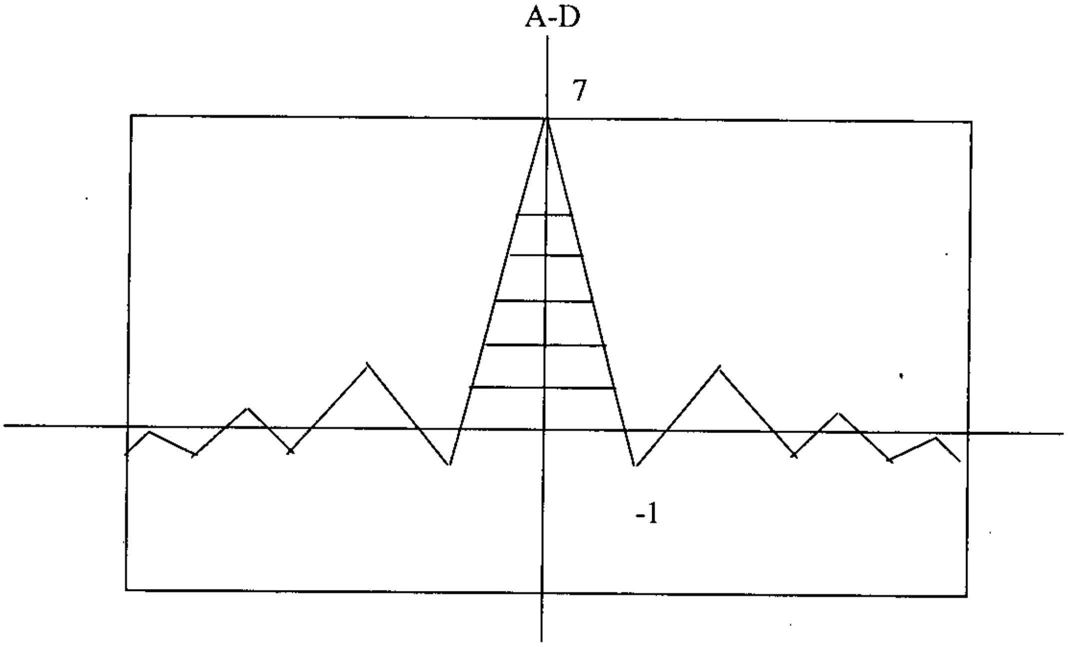

Fig 2.2(b) A peak amplitude due to auto-correlation

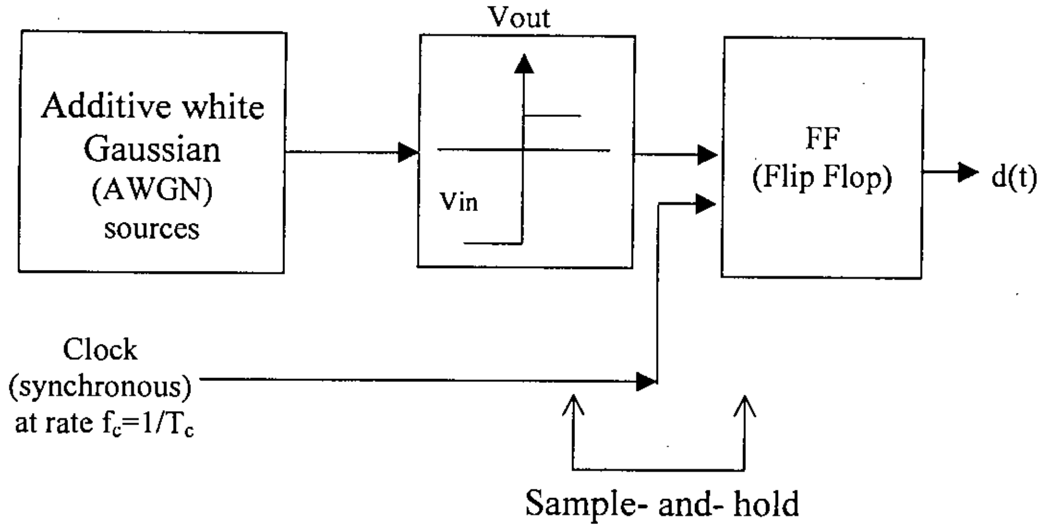

Fig 2.3 Pseudonoise (PN) binary data and random Synchronous data sequence generation concept

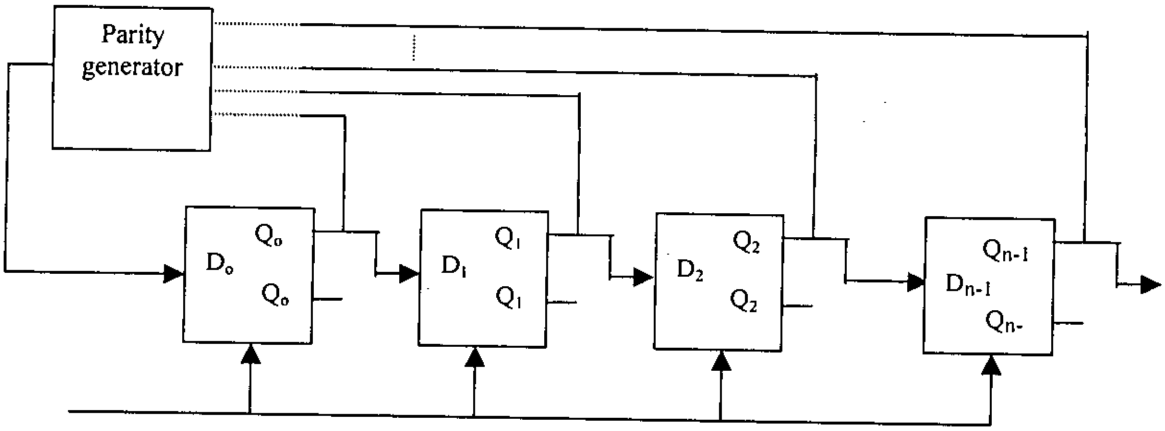

Fig 2.4 Hardware of a pseudonoise or PN generator

where N is the number of flipflops. A specific connection diagram of flip flop outputs to the parity generator input, shown in Fig.2.4, is illustrated in Table 2.1. The resultant maximal-length PN sequence L is between 7 and 32767 bits.

Independent sequence:

One possible logic design connection is illustrated in Table 2.1. There are many possible connections for the parity generator, which has small correlation with one another. The upper bound S of the number of independent sequence is given by

$$S \leq \frac{L-1}{N} \tag{2.5}$$

Periodic autocorrelation property:

The m-sequences have an interesting cyclic or periodic autocorrelation property. If w transform the binary (0,1) sequence of the shift register output to the binary (+1,-1) sequence by replacing each 0 by –1 and each 1 by +1, then the periodic correlation function is given by

$$\theta(\tau) = N = \begin{cases} 2^m - 1, \tau = 0 \\ -1, \tau \neq 0 \end{cases} \qquad (2.6)$$

and is the best possible periodic correlation function..

Table 2.1 Numerical values for sequence length and number of stages of shift register for PN sequence generation.

Number of stages N	Sequence Length $L = 2^N - 1$	S=Number of m sequences	Do for $L = 2^N - 1$ In Fig. 2.4
3	7	2	$Q_1 \otimes Q_2$
4	15	2	$Q_2 \otimes Q_3$
5	31	6	$Q_2 \otimes Q_4$
6	63	6	$Q_4 \otimes Q_5$
7	127	18	$Q_5 \otimes Q_6$
8	255	16	$Q_1 \otimes Q_2 \otimes Q_3 \otimes Q_7$
9	511	48	$Q_4 \otimes Q_8$
10	1023	60	$Q_6 \otimes Q_9$
11	2047	176	$Q_8 \otimes Q_{10}$
12	4095	144	$Q_1 \otimes Q_9 \otimes Q_{10} \otimes Q_{11}$
13	8191 .	630	$Q_0 \otimes Q_{10} \otimes Q_{11} \otimes Q_{12}$
14	16383	756	$Q_1 \otimes Q_{11} \otimes Q_{12} \otimes Q_{13}$
15	32767	1800	$Q_{13} \otimes Q_{14}$

For an L=3 stage shift register generator, generating a 7 bit ($m = 2^{L-1}$) maximal length pseudorandom code, with a chip rate of 10Mc/s and a 7bit reference sequence 1110010, the table of the number of agreements(A) and disagreements (D) by lining up the shifted autocorrelation code sequence in one bit increments is like following (Table 2.2):

Table2.2 The number of agreements(A) and disagreements (D) generating a 7 bit maximal length pseudorandom code;

Reference Sequence: 1110010.

Shift	**Sequence**	**Agreements(A)**	**Disagreements(D)**	**A-D**
0	1110010	7	0	7
1	0111001	3	4	-1
2	1011100	3	4	-1
3	0101110	3	4	-1
4	0010111	3	4	-1
5	1001011	3	4	-1
6	1100101	3	4	-1

Gold sequence:

In contrast to simple m-sequences, Gold-sequences are suitable for multiple user CDMA systems. They offer a large number of sequence sets with good crosscorrelation properties between the single sequences.

The gold sequences are generated by modulo-2 addition of two m-sequences clocked by the same chip-clock shown in Fig 2.5. The most significant key in Gold sequence design is that only special pairs of m-sequences deliver the desired correlation properties. Since both m-sequences have equal length L and use the same clock, the created Gold sequence is of length L and use the same clock, the created Gold sequence is of length L as well;

however it is no longer maximal. Let n be the number of stages in each m-sequence generator. The gold sequence length will be

$$L = 2^n - 1 \tag{2.7}$$

In the Fig. 2.5, it has been shown that the possible number of different Gold sequences created with the two m sequence generator setup. It can be shown that for any shift in the initial conditions between the two m-sequences a new gold sequence is generated. Since each m-sequence is of length L, the same number of different shifts between the two m-sequence is available.

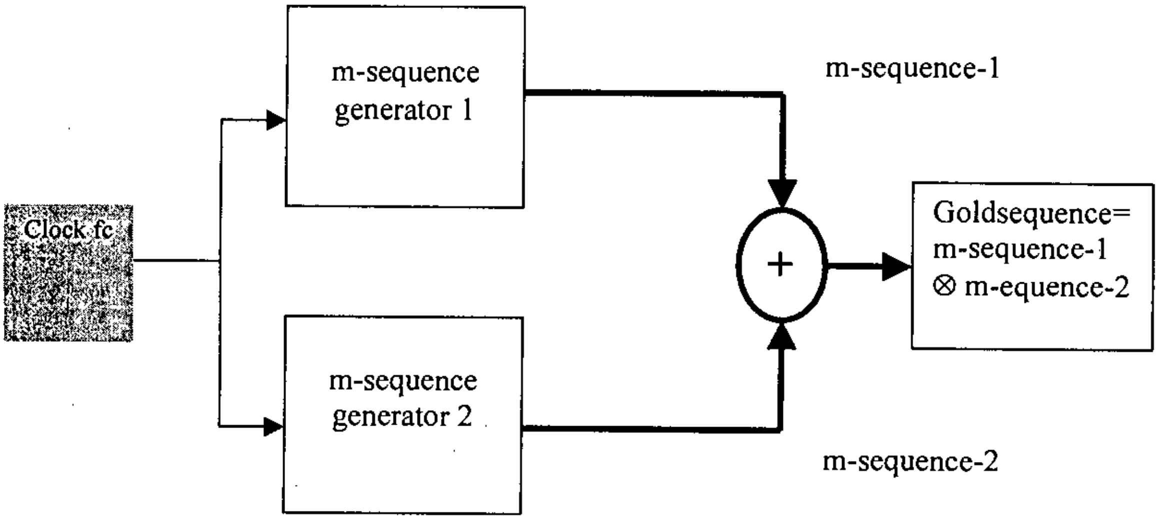

Fig 2.5 Block diagram of Gold sequence Generator

Thus a Gold sequence generator combining two different m-sequences can create a number of different $L = 2^N - 1$ Gold sequences. With a proper choice of the m-sequence pairs the desired low cross correlation can be maintained between all created Gold sequences.

The use of Gold sequences permits the transmission to be asynchronous. The receiver can synchronize using the auto-correlation property of the Gold sequence.

2.3 Optical CDMA

In the recent years the explosive growth of the internet, growing application of high speed multimedia such as data, voice, video and so on, demands on both the capacity and functionality of optical communication system and networks. Most work is focused on the use of wavelength division multiplexing (WDM), optical time division multiplexing (OTDM) or a hybrid approach to achieve tera bit per second channel capacity. Now a days, interest is beginning to grow in investigating alternative multiplexing scheme such as optical code division multiple access (OCDMA) that can further enhance the functionality of optical networks [32], [33]. CDMA has been applied with great success to the field of mobile communications but has only recently generated significant interest in the optical domain. The particular attractions of optical CDMA (OCDMA) include

- the capacity for higher connectivity,
- more flexible bandwidth usage,
- higher granularity and scalability within optical network,
- improved crosstalk performance,
- asynchronous access,
- and potential for improved system security.

OCDMA is spread spectrum technique that permits a large number of separate users to share the same extended transmission optical bandwidth but to be individually addressable through the allocation of specific address code signature sequence with good correlation properties[35]. The encoding can be performed either in the time domain [direct sequence (DS-CDMA)] or frequency domain [frequency hopping (FH-OCDMA)]. In DS-CDMA each data bit to be transmitted is defined by a code composed of sequence of pulses. The individual pulses comprising the coded bits are commonly referred to as chips. The coded bits are then broadcast onto the network but are only received by the simple match filtering within the receiver. By contrast, in FH-OCDMA, the carrier frequency of the chip is changed according to a well defined code sequence that can once again be suitably identified by an appropriate receiver.

2.4 System Description of the work:

In the present research work, asynchronous sequence inversed keyed (SIK) modulation-demodulation technique is considered for optical fiber CDMA network.

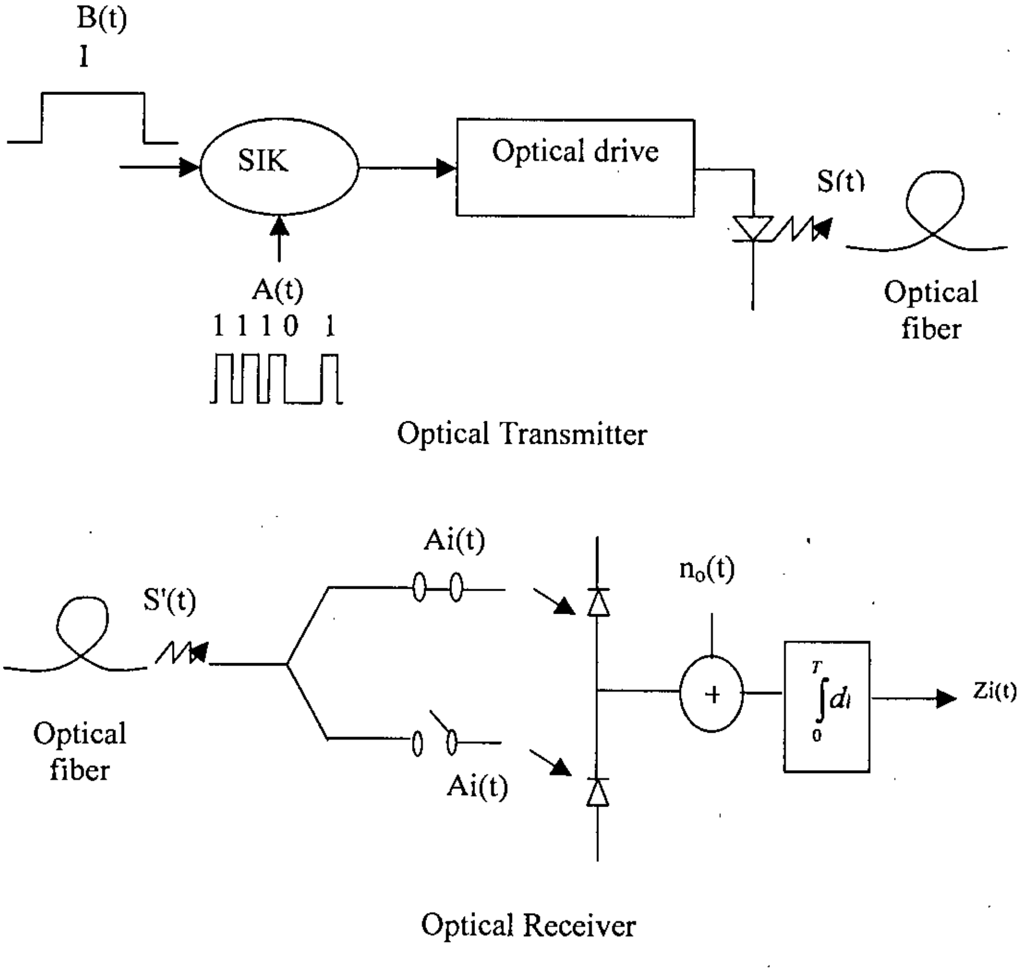

Fig 2.6 Schematic block diagram for an Optical CDMA transmission system with Sequence Inversed Keyed (SIK) optical correlator receiver.

In the transmitter a user's data is modulated either by a unipolar signature sequence or by it's complement, depending on whether it is a '0' or '1', respectively. In this scheme, an optically switched correlator receiver based on the principle of unipolar-bipolar correlation, has been used as shown in (Fig.2.6). Unipoloar-bipolar correlation allows conventional bipolar signature sequences to be used in SIK DS- CDMA optical fiber network using noncoherent transmission and direct detection. For the same bandwidth expansion factor conventional bipolar signature sequence exhibits larger set sizes thereby supporting more network subscriber and lower multiple access interference (MAI), thereby supporting more simultaneous users, than either prime code [23] or optical orthogonal code [10].

In the receiver a bipolar reference sequence is correlated directly with the channel unipolar signature sequence in order to recover the original data. This unipolar bipolar correlation is practically realized in an all-optical correlator, by separating the bipolar reference sequence into two complementary unipolar reference sequences which provide unipolar switching functions to despread the optical channel signal. Unipolar signal can be realized optically by Mach -Zehnder interferometers [25]. The despread optical signal is subtracted in a balanced pin diode receiver and then integrated over a data bit period prior to zero threshold detection.

2.5 System Analysis:

At the transmitter a sequence of unit amplitude rectangular data bits each of duration T, denoted as B(t), is used to sequence inverse key A(t), where A(t) is a period sequence of N unit amplitude, rectangular chips each of duration T_c and $N=T/T_c$, such that either the sequence A(t) or it' s complement $\bar{A}(t)$ is transmitted for a 1 or 0, data bit, respectively. The SIK signal then drives a suitable optical light source such as an light emitting diode (LED) or Laser diode. The LED or Laser diode output is given by [25]

$$S(t) = \sum_{k=1}^{K} \sum_{l=0}^{N-1} 2P_T B_k(t) \otimes A_k(t - lT_C) \tag{2.8}$$

where P_T is the peak incident chip optical power for the k-th user at the transmitter output, l is l-th chip delay, K is number of simultaneous users and $\otimes$ is the operator that denotes sequence inverse keying (SIK) modulation such that either the sequence A(t) or its complement $\bar{A}(t)$ is transmitted for a 1 or 0, data bit, respectively.

This output is then transmitted through the optical fiber. During propagation through the fiber, the optical pulse undergoes dispersion due to fiber chromatic dispersion. If $Sout_k(t)$ represents the output pulse shape due to fiber chromatic dispersion, for the K-th user, then the output of the fiber can be expressed by

$$S'(t) = \sum_{k=1}^{K} \sum_{l=0}^{N-1} P_R B_k(t) Sout_k(t) \otimes A_k(t - lT_C) \tag{2.9}$$

where the exact expression of Sout(t) is given by

$$Sout(t) = \sum_{k=1}^{K} \sum_{l=0}^{N-1} 1/2\{Sc(t - lTc) + Ss(t - lTc) + j \operatorname{sgn} \gamma [Sc(t - lTc) - Ss(t - lTc)]\} \tag{2.10}$$

$$S_c(t) = C\left(\frac{t + Tc/2}{Tc\sqrt{\gamma}}\right) - C\left(\frac{t - Tc/2}{Tc\sqrt{\gamma}}\right) \tag{2.11}$$

$$Ss(t) = S\left(\frac{t + Tc/2}{Tc\sqrt{\gamma}}\right) - S\left(\frac{t - Tc/2}{Tc\sqrt{\gamma}}\right) \tag{2.12}$$

where,

Υ= Chromatic dispersion index of the fiber= $\frac{\lambda^2}{\pi c} D b_C^{\,2} L$ (2.13)

λ=optical wavelength corresponding to the carrier frequency.

D=Fiber chromatic dispersion index coefficient

bc=chip rate

L=fiber length

$$C(x)=\sqrt{\pi/2}\int_{o}^{x}\cos t^{2}.dt=J_{1/2}\left(\pi x^{2}/2\right)+J_{5/2}\left(\pi x^{2}/2\right)+J_{9/2}\left(\pi x^{2}/2\right)+----$$

(2.14)

$$S(x)=\sqrt{\pi/2}\int_{o}^{x}\sin t^{2}.dt=J_{3/2}\left(\pi x^{2}/2\right)+J_{7/2}\left(\pi x^{2}/2\right)+J_{11/2}\left(\pi x^{2}/2\right)+----$$

(2.15)

The approximate expression for Sout(t) is given by

$$Sout\,(t)=\sum_{k=1}^{K}\sum_{l=0}^{N-1}\frac{1}{\sqrt{\pi\gamma}}e^{-j[(1/\lambda)(\frac{(t-lTc)}{Tc}-(\pi/4)\mathrm{sgn}\,\lambda}\sin c\frac{(t-lTc)}{\pi\lambda\,Tc}$$

(2.16)

for $.3 \le \gamma \le 1$

where, $\sin c(x) = \frac{\sin(\pi x)}{\pi x}$

At the output of the fiber, the optical CDMA signal is received by an optical correlator receiver with balanced photodetectors. The output of the photodetector is passed through an integrator. Then the output of the correlator, matched to the ith user, is given by

$$Zi(t)=\frac{RP_R}{2}\int_0^T\sum_{k=1}^{K}\sum_{l=0}^{N-1}B_k(t)Sout_k(t)\otimes A_k(t-lT_c)\{Ai(t-lTc)-\overline{Ai(t-lTc)}\}.dt$$

$$+\int_0^T n_o(t)dt \qquad (2.17)$$

where R is responsivity of each photodiode *(pin)*, $\bar{A}i(.)$ is the complement of Ai(.) and $n_o(t)$ is the total channel noise at the correlator output, P_R is the received optical power which is related to the transmitted power as

$$P_R = P_T - P_f \qquad (2.18)$$

where, P_f is the fiber loss.

Since $a_i(.)= \{Ai(.)- \bar{A}i(.)\}$ and $Bk(.)oAk(.)=\{1+b_k(.)a_k(.)\}/2$ and $S_{out}(.)=s_{out}(.)$, where $a_i(.)$, $b_k(.)$ and $s_{out}(.)$ are bipolar forms of Ai(.) , Bk(.) and Sout(.) respectively, then eq (2.17) reduces to

$$Zi'(t)=\frac{RP_R}{2}\int_0^{Tb}\sum_{k=1}^{K}\sum_{l=0}^{N-1}\{\frac{1+b_k(t-lTc)a_k(t-lT_c)}{2}.sout_k(t-lTc)a_i(t-lTc)\}dt$$

$$+\int_0^{T_b} n_o(t)dt \qquad (2.19)$$

$$=\frac{RP_R}{4}\int_0^{Tb}\sum_{l=0}^{N-1}\{sout_i(t-lTc)a_i(t-lTc)\}dt+\frac{RP_R}{4}\int_0^{T_b}\sum_{l=0}^{N-1}sout_i(t-lTc)dt$$

$$(2.20)$$

$$+\frac{RP_R}{4}\int_0^{Tb}\sum_{\substack{k\neq i\\k=1}}^{K}\sum_{l=0}^{N-1}\{b_k(t-lTc)sout_k(t-lTc)a_k(t-lT_c)a_i(t-lTc)\}dt+\int_0^{T_b}n_o(t)dt$$

The first term in eqn. (2.20) is the offset effect which is removed by using balanced signature sequence. The second and third term in eqn. (2.20) are the in phase autocorrelation peak and multiple access interference (MAI), respectively.

The mean of Z'(t) is given as,

$$U = \frac{RP_R}{4T_b} \int_0^{T_b} \sum_{l=0}^{N-1} sout_i(t - lTc)dt \tag{2.21}$$

The variance of interference due to MAI, is given by [25]

$$\sigma^2 = U^2 . \frac{2(K-1)}{3N} \tag{2.22}$$

The variance of noise, $n_o(t)$ is given by

$$No = N_{th} + N_{sh} \tag{2.23}$$

N_{th} is the receiver thermal noise which is given by

$$N_{th} = (4.k.T.)Br.R_L \tag{2.24}$$

and N_{sh} is the photodetector shot noise which is given by

$$N_{sh} = 2qRKP_R / (4T); \tag{2.25}$$

where,

k= Boltzman constant

T=Receiver temperaure (^oK)

Br=Receiver bandwidth=1/T

R_L=Load resistence of the receiver

K =number of simultaneous users

q =electron charge(1.6e-19)

The signal to noise ratio at the correlator output can be obtained as

$$SNR = \frac{U^2}{\sigma^2 + No} \qquad (2.26)$$

For single user, variance of interference is zero.

For the calculation of SNR without dispersion the pulse shape of Sout(t) is rectangular and its amplitude is 1. So, in this case, if the number of 1 in a sequence is n and the number of chips in a bit is n′, then the value of mean, Ur is

$$Ur = \frac{RP_R}{4} \times \frac{n}{n'} \qquad (2.27)$$

Hence, the bit error rate for the OCDMA transmission system is then given by [47]

$$BER = (1/2)erfc(\frac{\sqrt{SNR}}{\sqrt{2}}) \qquad (2.28)$$

Chapter 3

Results and Discussion

Following the analytical formulation presented in Sec. 2.5 we evaluate the performance of an optical CDMA transmission system using m-sequence and gold sequence of length of 7 and 32 chip respectively, at a chip rate of 10Gchip/sec, using single mode fiber. For the transmission and receiving blocks shown in Fig. 2.6, the effect of fiber chromatic dispersion on the system performance is evaluated in terms of eye penalty as well as the penalty from the bit error rate performance curves at a chip rate of 10Gchip/sec with fiber chromatic dispersion coefficient, D =16 ps/km-nm. The other parameters of the SM fiber used for numerical computation are wavelength = 1550 nm, Photodetector responsivity = .85A/W, load resistance of the receiver = 50 ohm.

Simulation is carried out to determine the chip waveform at the output of the optical correlator with dual detector configuration. The plots of chip waveforms at the input and output of correlator are shown in Fig. 3.1 and Fig. 3.2, respectively for 32 chip gold sequence 00001010101111000010100001100001, for fiber chromatic dispersion index, γ = 1. The rectangular chip sequence is distorted at the correlator input after propagating through the SM fiber and there is interchip interference due to fiber chromatic dispersion. At the output of the correlator the negative signal results due to dual photodetector configuration of the correlator which provides negative output due to '0' chips.

For an m-sequence 1110010 of length 7, we simulate the eye diagram shown in Fig. 3.3 for same system parameter while fiber chromatic dispersion index, γ =.05. From this plot it is evident that there exists an effect of dispersion on the output chip waveform as well as eye closure. Similar plots are depicted in Fig 3.4 to Fig 3.6 for γ=0.1, 0.2 and 0.5 respectively. It is now clear from the figure that as γ increases there is a deterioration in eye diagram resulting in eye closure. The amount of eye closure is directly proportional to the amount of dispersion . The penalty due to dispersion is evaluated as

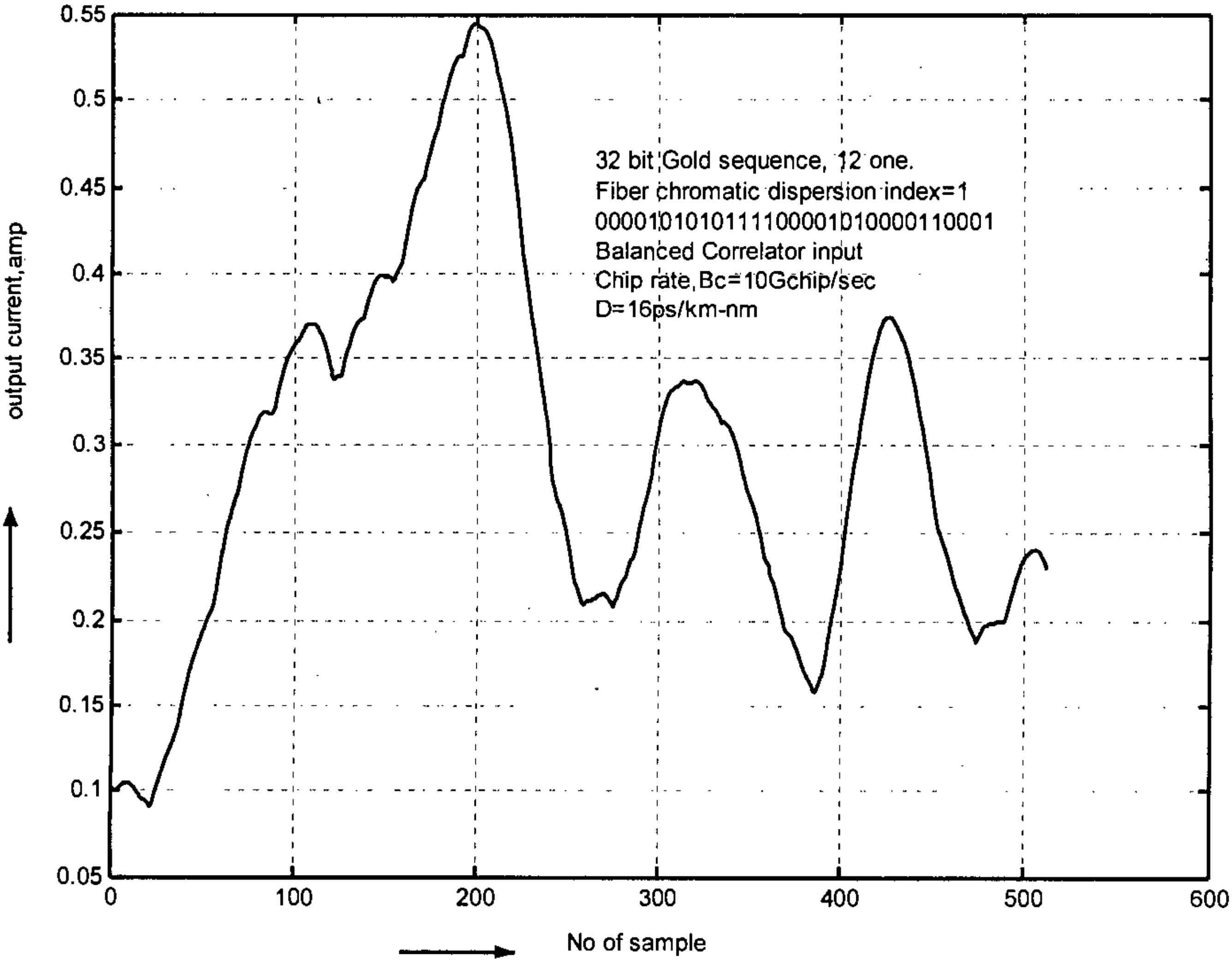

Fig. 3.1 The plot of chip waveform at the input of the optical correllator with dual detector configuration of an optical CDMA transmission system with 32 chip Gold sequence 00001010101111000010100001 10001 and DD SIK receiver when the value of fiber chromatic dispersion index,γ= 1, at a chip rate, Bc=10Gchip/sec, with fiber chromatic dispersion, D = 16ps/km-nm.

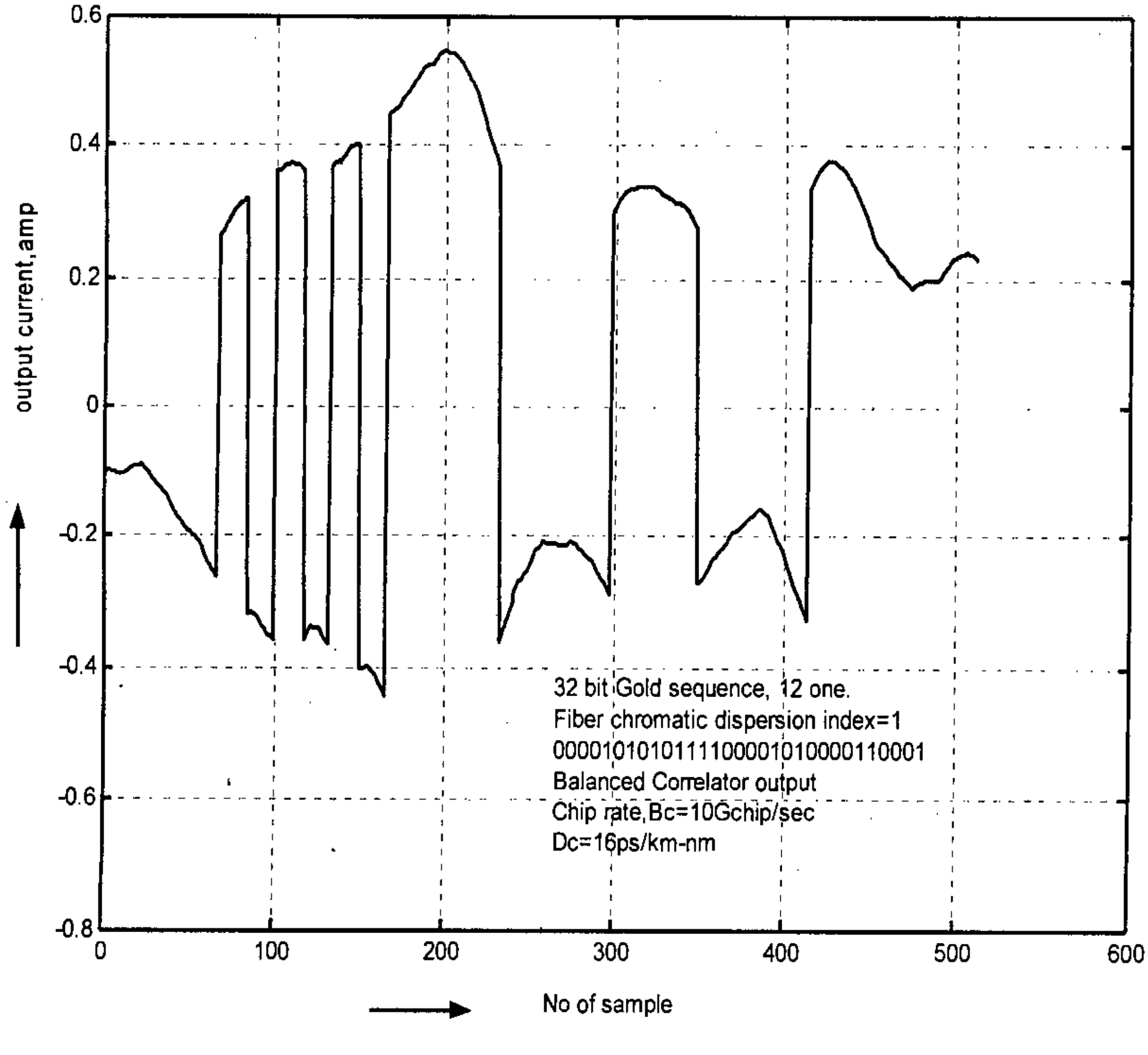

Fig. 3.2 The plot of chip waveform at the output of the optical correllator with dual detector configuration of an optical CDMA transmission system with 32 chip Gold sequence 00001010101111000010100001100001 and DD SIK receiver when the value of fiber chromatic dispersion index,γ = 1, at a chip rate, Bc = 10Gchip/sec, with fiber chromatic dispersion, D = 16ps/km-nm.

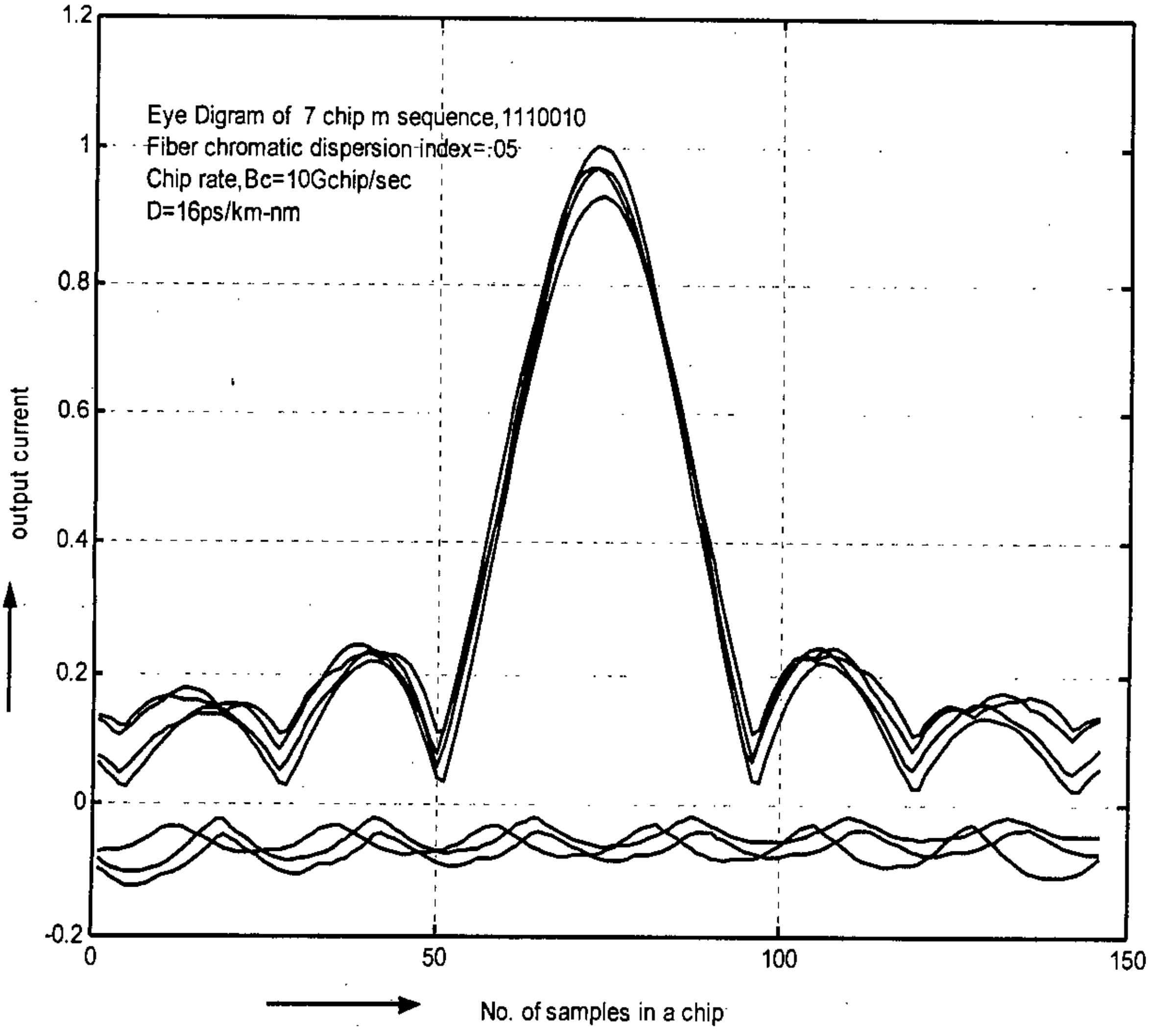

Fig. 3.3 The eye diagram of an Optical CDMA transmission system with 7 chip m-sequence and DD SIK receiver when the value of fiber chromatic dispersion index, γ=0.05 and the reference sequence chip sequence is 1110010, at a chip rate, Bc=10Gchip/sec, with fiber chromatic dispersion, D=16ps/km-nm.

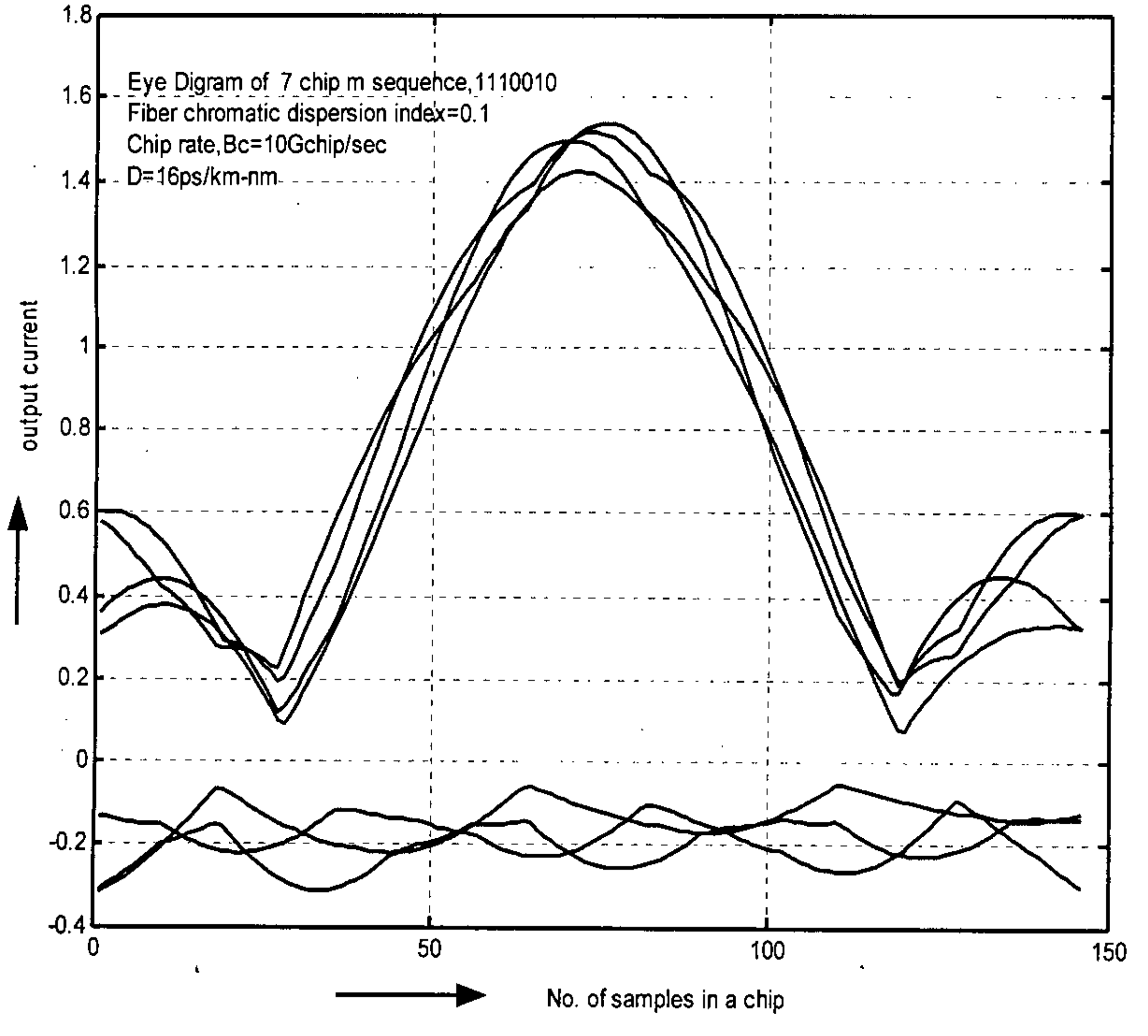

Fig. 3.4 The eye diagram of an Optical CDMA transmission system with 7 chip m-sequence and DD SIK receiver when the value of fiber chromatic dispersion index, γ = 0.1 and the reference sequence chip sequence is 1110010. At a chip rate, Bc = 10Gchip/sec, with fiber chromatic dispersion, D = 16ps/km-nm.

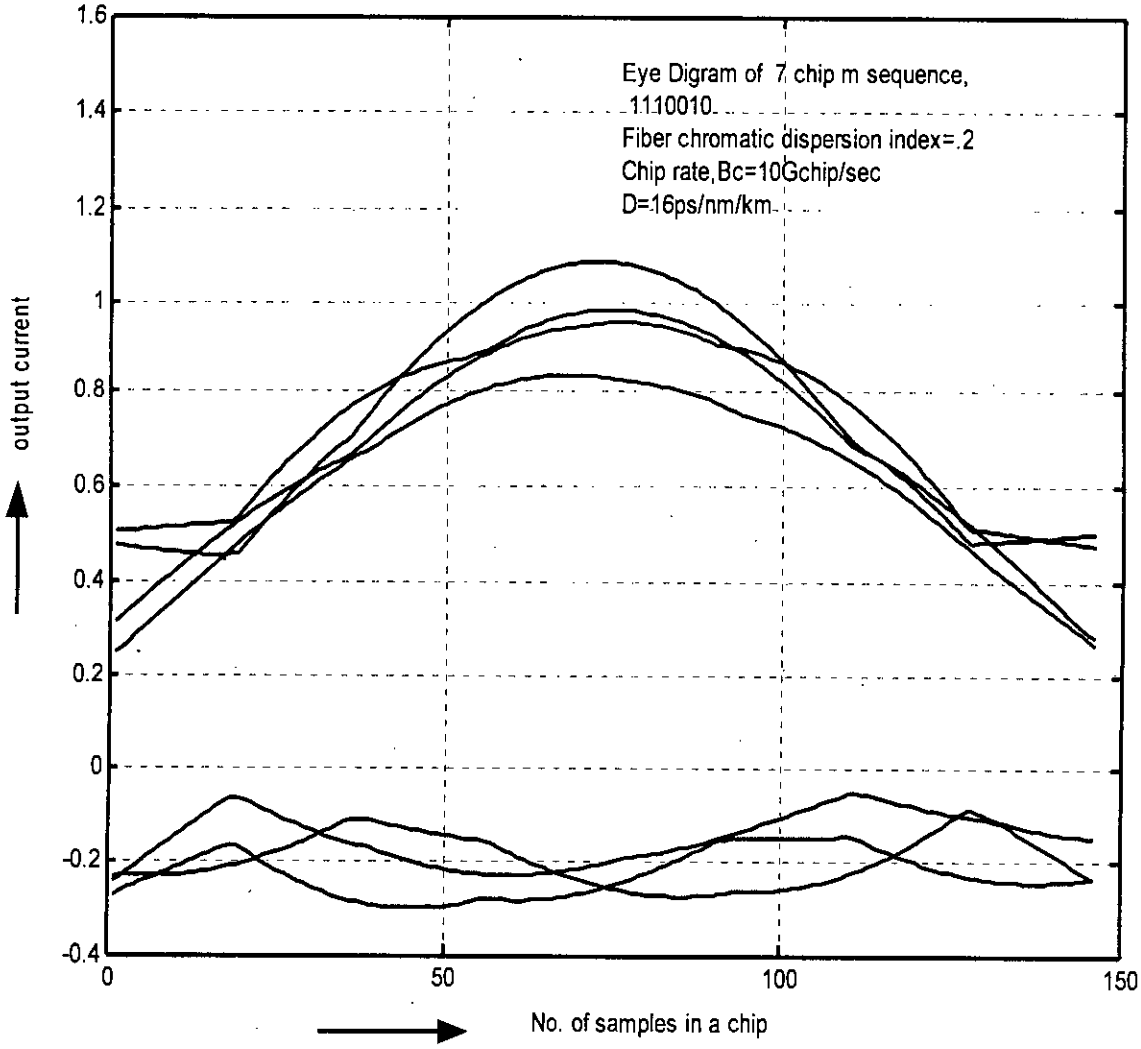

Fig. 3.5 The eye diagram of an Optical CDMA transmission system with 7 chip m-sequence and DD SIK receiver when the value of fiber chromatic dispersion index, γ= 0.2 and the reference sequence chip sequence is 1110010, at a chip rate, Bc = 10Gchip/sec, with fiber chromatic dispersion, D = 16ps/km-nm.

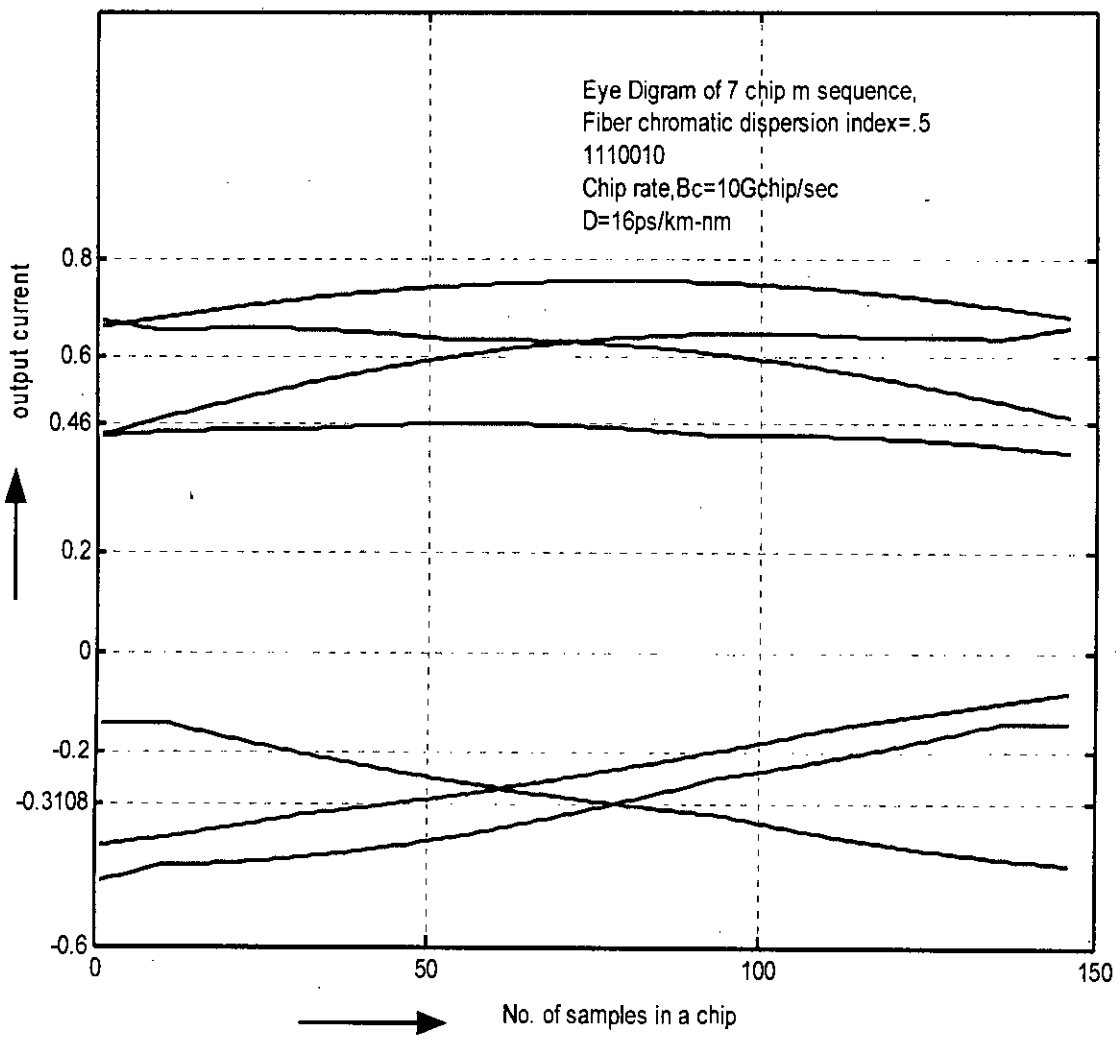

Fig. 3.6 The eye diagram of an Optical CDMA transmission system with 7 chip m-sequence and DD SIK receiver when the value of fiber chromatic dispersion index, γ = 0.5 and the reference sequence chip sequence is 1110010, at a chip rate, Bc = 10Gchip/sec, with fiber chromatic dispersion, D = 16ps/km-nm.

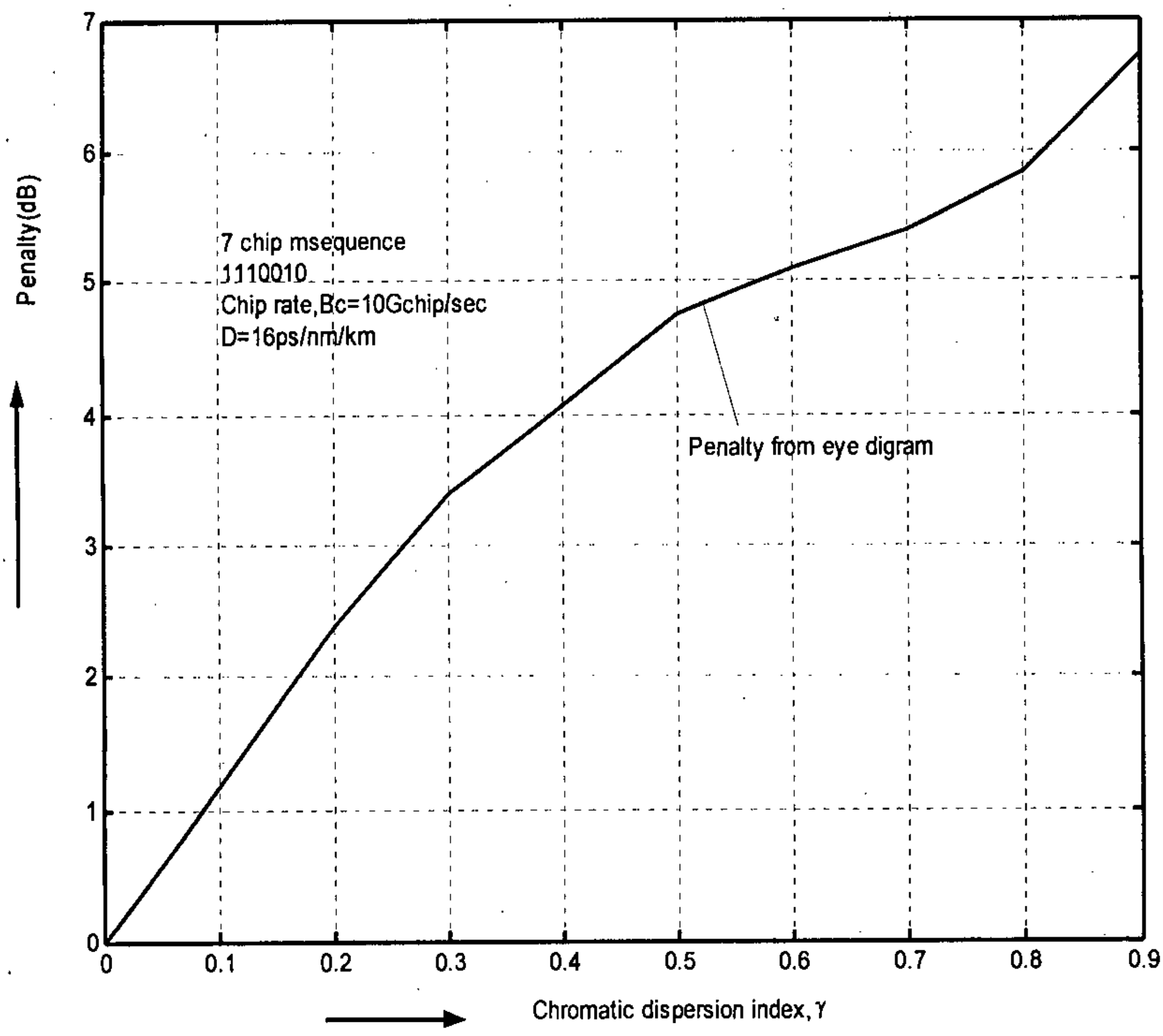

Fig. 3.7 The plot of penalty of the 7 chip m-sequence 1110010 versus different values of dispersion index, γ obtained from the eye diagrams of Fig. 3.3 to Fig. 3.6 for an OCDMA DD-SIK receiver, at a chip rate, Bc = 10Gchip/sec, with fiber chromatic dispersion, D = 16ps/km-nm and bit error rate, BER=10^{-9}.

$$Penalty(db) = 20\log\frac{a}{b} \qquad 3.1$$

whereas, a = opening of eye without dispersion

and b = opening of eye with dispersion.

The plots of eye closure penalty due to dispersion is depicted in Fig 3.7. The plot reveals that there is a considerable amount of power penalty due to dispersion.

Following the analytic formulation presented in Sec. 2.5, the bit error rate performance results from an optical CDMA transmission system at a chip rate of 10 Gchip/sec is depicted in Fig 3.8 in the presence of receiver thermal noise and shot noise considering the effect of fiber chromatic dispersion for a 7 chip m-sequence consisting of 1110010. The bit error rate is plotted as a function of received power P_R (dBm) with the values of the fiber chromatic dispersion index, γ ranging from .05 to 1. The bit error rate curve for $\gamma=0$ is plotted as the reference receiver sensitivity which is defined as the optical power required to achieve a BER of 10^{-9}. The figure reveals that for a constant value of γ, bit error rate decreases with the increase in received power. It is also observed that a higher received power is needed with the increase of γ in order to maintain a specific BER value of 10^{-9} due to the effect of dispersion.

Similarly, Fig 3.9 to Fig. 3.14 depict plots of BER versus received power P_R, with fiber chromatic dispersion index, γ as a parameter for six more types of 7 chip m-sequence which are 0111001, 1011100, 0101110, 0010111, 1001011 and 1100101.

Fig 3.15 depicts the various plots of power penalty as a function of fiber chromatic dispersion index, γ, for the seven, 7 chip m-sequence obtained from Fig 3.8 to Fig 3.14. The power penalty increases continuously with the increase of fiber chromatic dispersion. It is found that for the chip sequence 1001011 and 1100101, the system suffers more penalty.

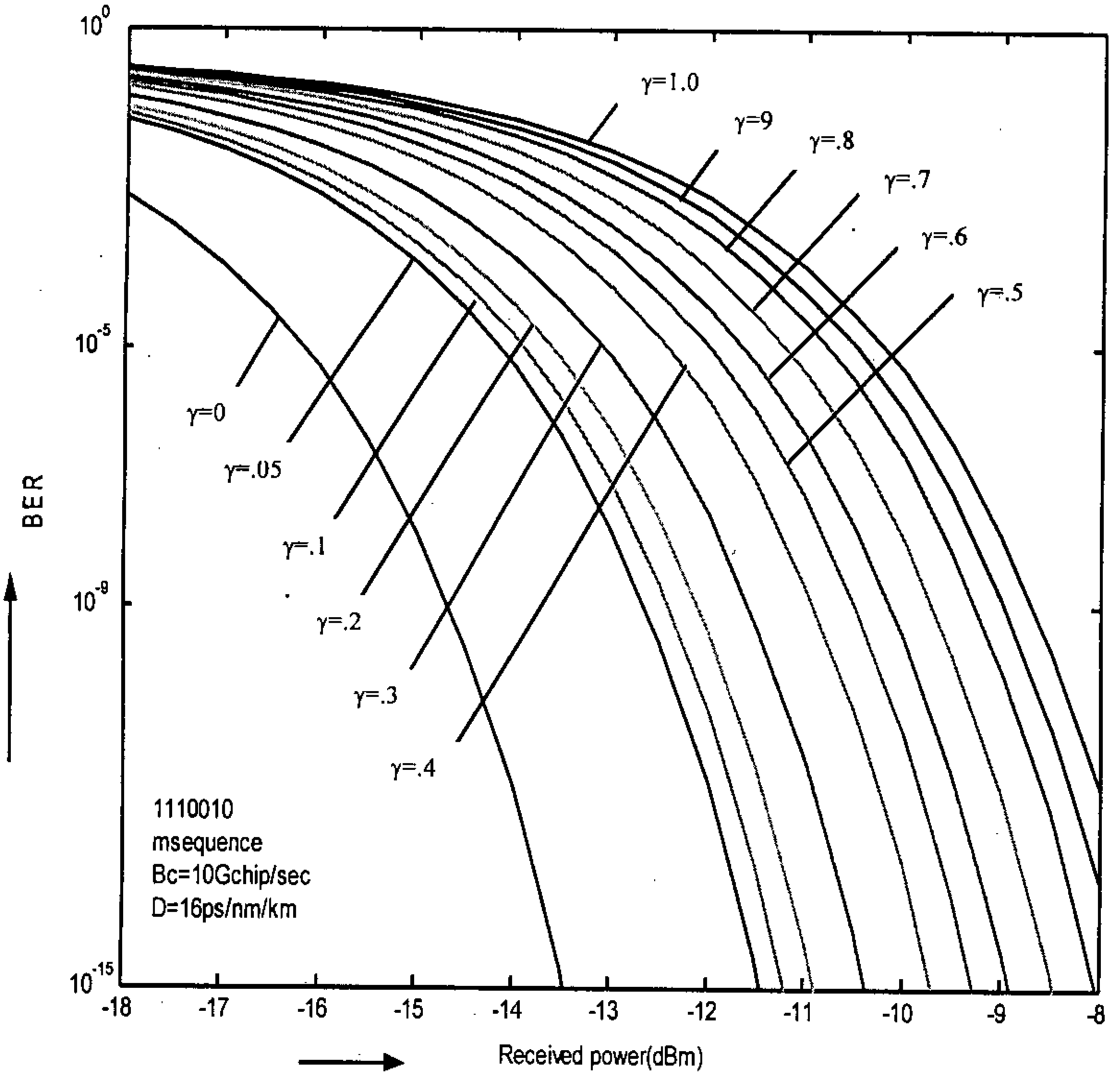

Fig. 3.8 The bit error rate (BER) performance of an optical CDMA transmission system with 7 chip m-sequence and DD-SIK receiver for different values of fiber chromatic dispersion index, γ. when the reference chip sequence is 1110010 at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm.

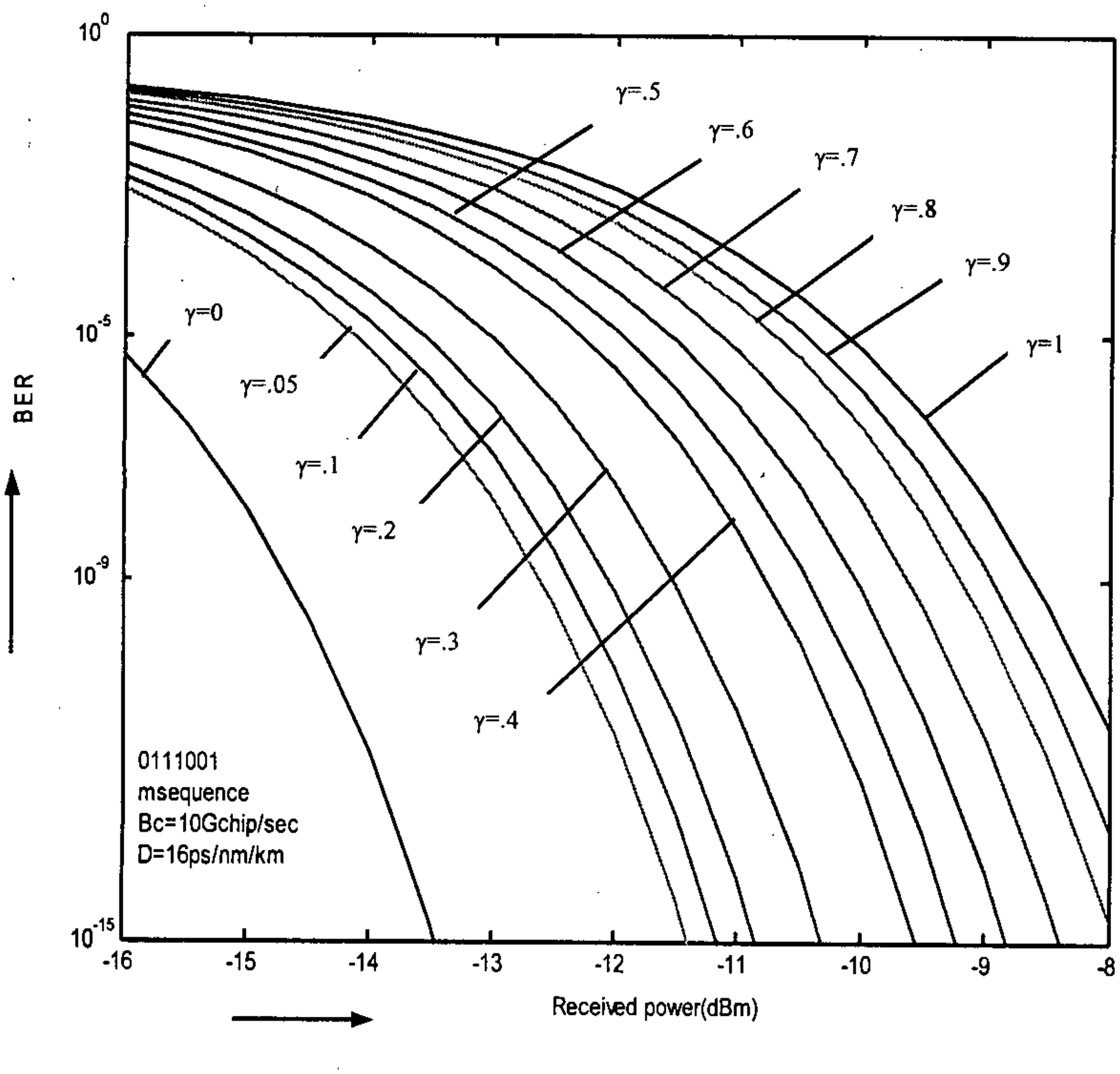

Fig. 3.9 The bit error rate (BER) performance of an optical CDMA transmission system with 7 chip m-sequence and DD-SIK receiver for different values of fiber chromatic dispersion index, γ when the chip sequence is 0111001 which is 1 chip right shifted from the reference sequence 1110010, at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm.

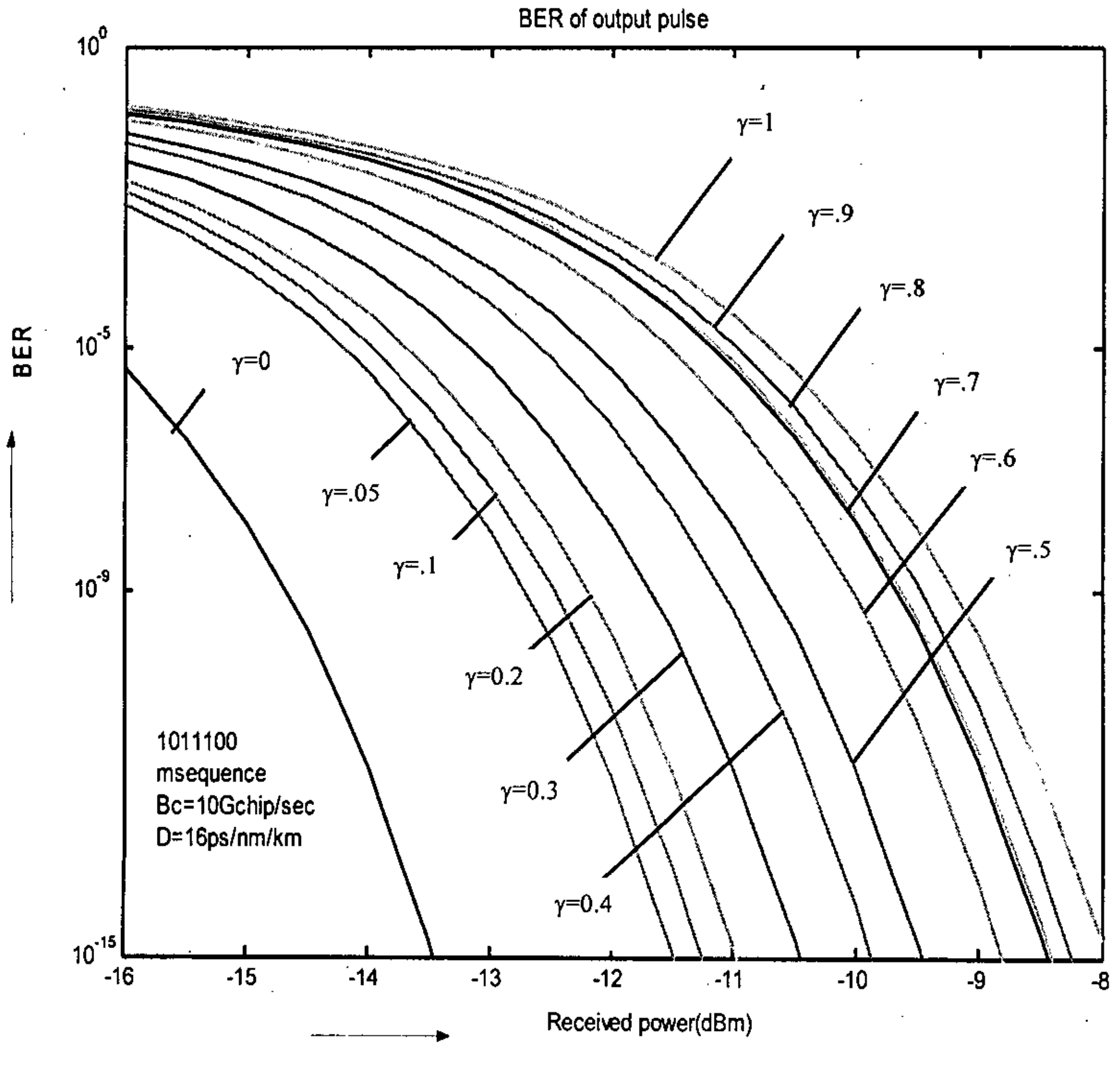

Fig. 3.10. The bit error rate (BER) performance of an optical CDMA transmission system with 7 chip m-sequence and DD-SIK receiver for different values of fiber chromatic dispersion index, γ when the chip sequence is 1011100 which is 2 chip right shifted from the reference sequence 1110010, at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm

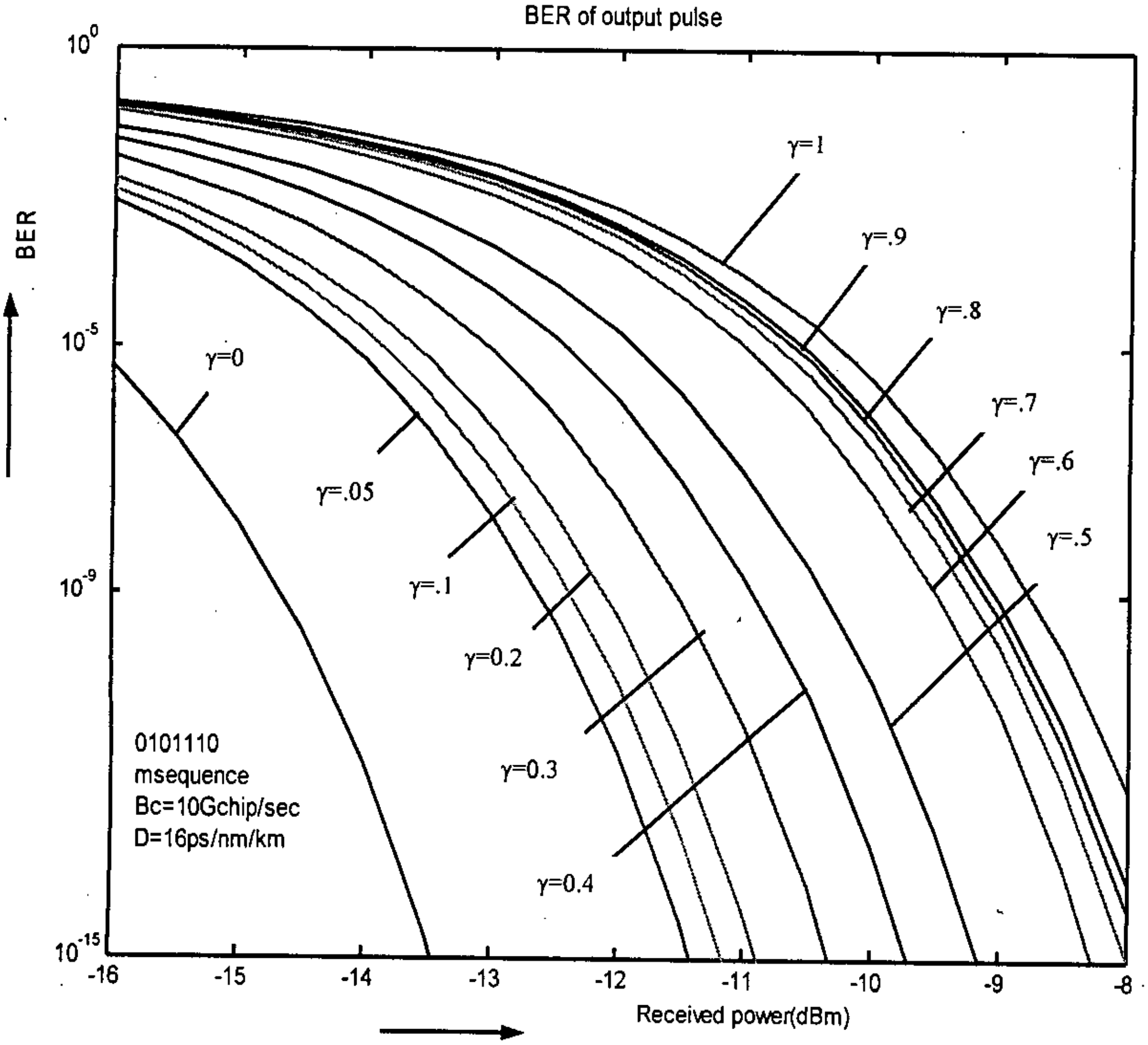

Fig. 3.11 The bit error rate (BER) performance of an optical CDMA transmission system with 7 chip m-sequence and DD-SIK receiver for different values of fiber chromatic dispersion index, γ when the chip sequence is 0101110 which is 3 chip right shifted from the reference sequence 1110010, at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm

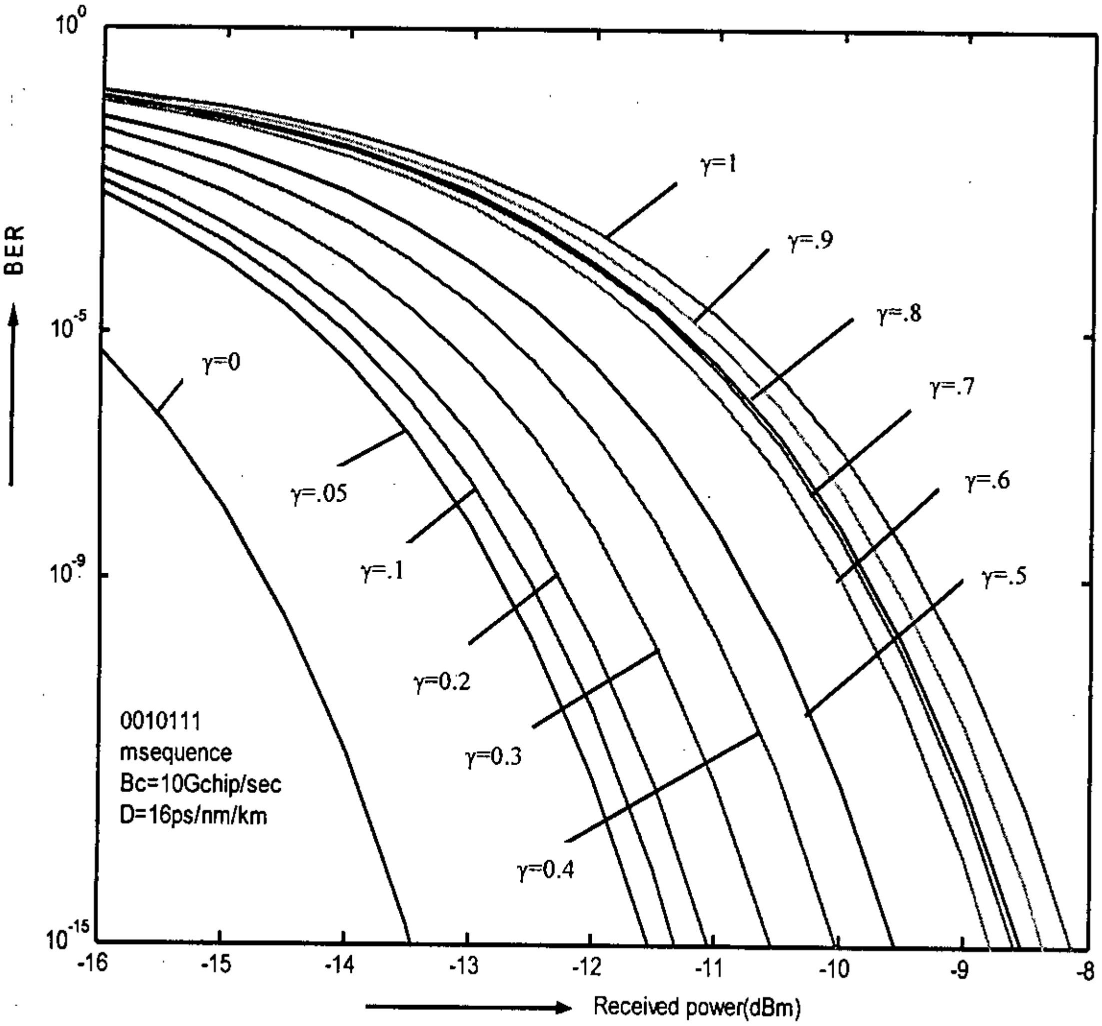

Fig. 3.12 The bit error rate (BER) performance of an optical CDMA transmission system with 7 chip m-sequence and DD-SIK receiver for different values of fiber chromatic dispersion index, γ when the chip sequence is 0010111 which is 4 chip right shifted from the reference sequence 1110010, at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm.

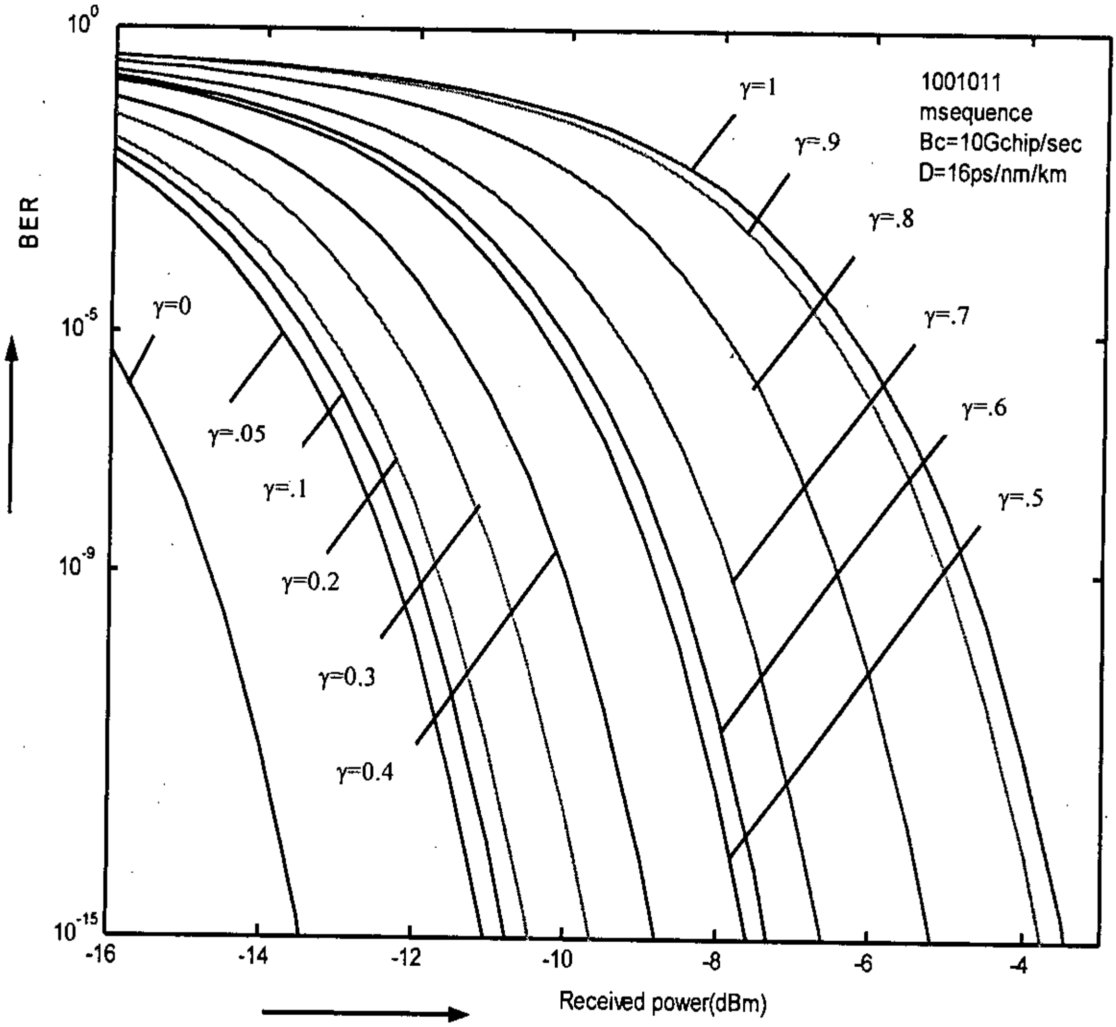

Fig. 3.13. The bit error rate (BER) performance of an optical CDMA transmission system with 7 chip m-sequence and DD-SIK receiver for different values of fiber chromatic dispersion index, γ when the chip sequence is 1001011 which is 5 chip right shifted from the reference sequence 1110010, at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm.

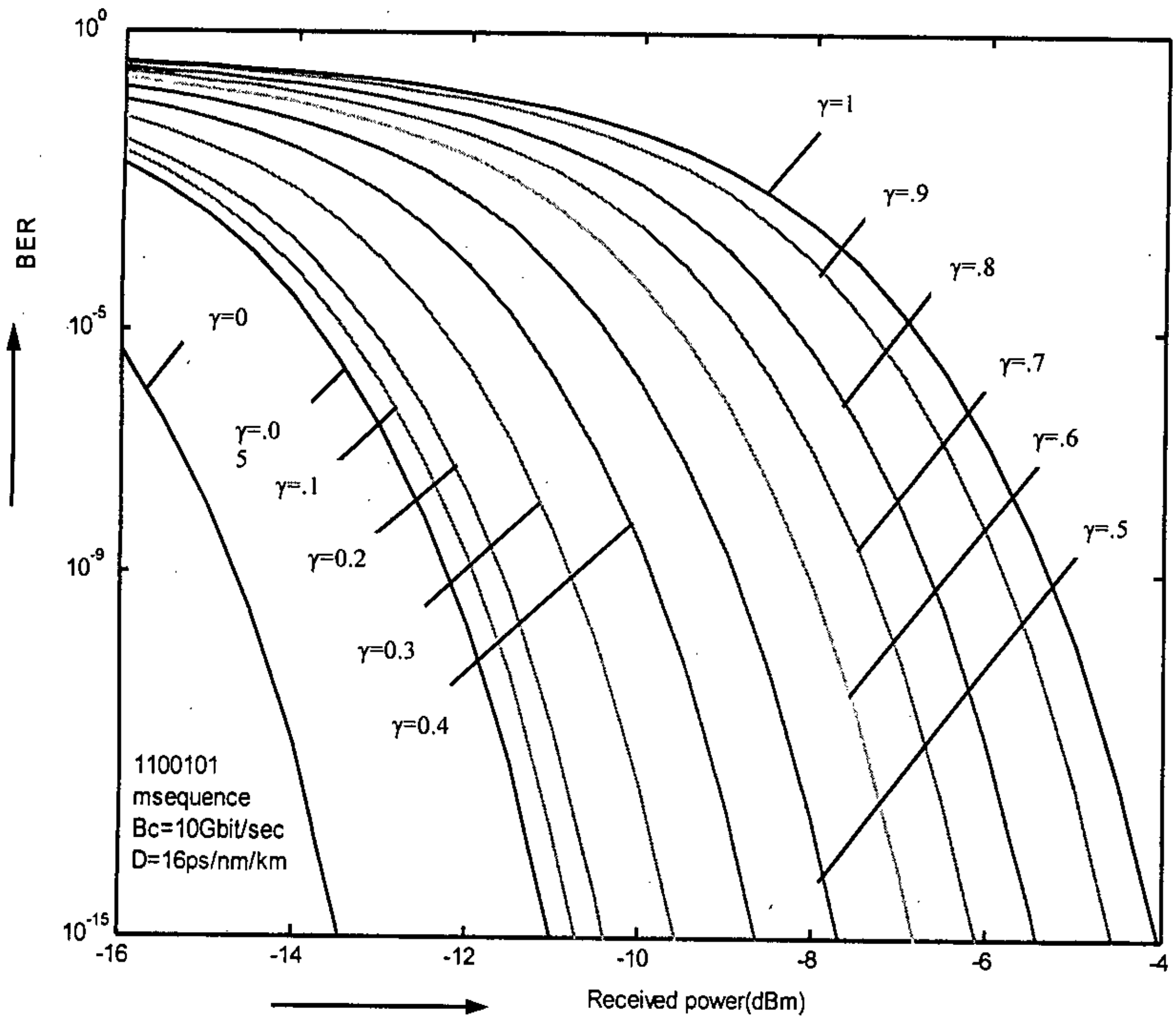

Fig. 3.14 The bit error rate (BER) performance of an optical CDMA transmission system with 7 chip m-sequence and DD-SIK receiver for different values of fiber chromatic dispersion index, γ when the chip sequence is 1100101 which is 6 chip right shifted from the reference sequence 1110010, at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm.

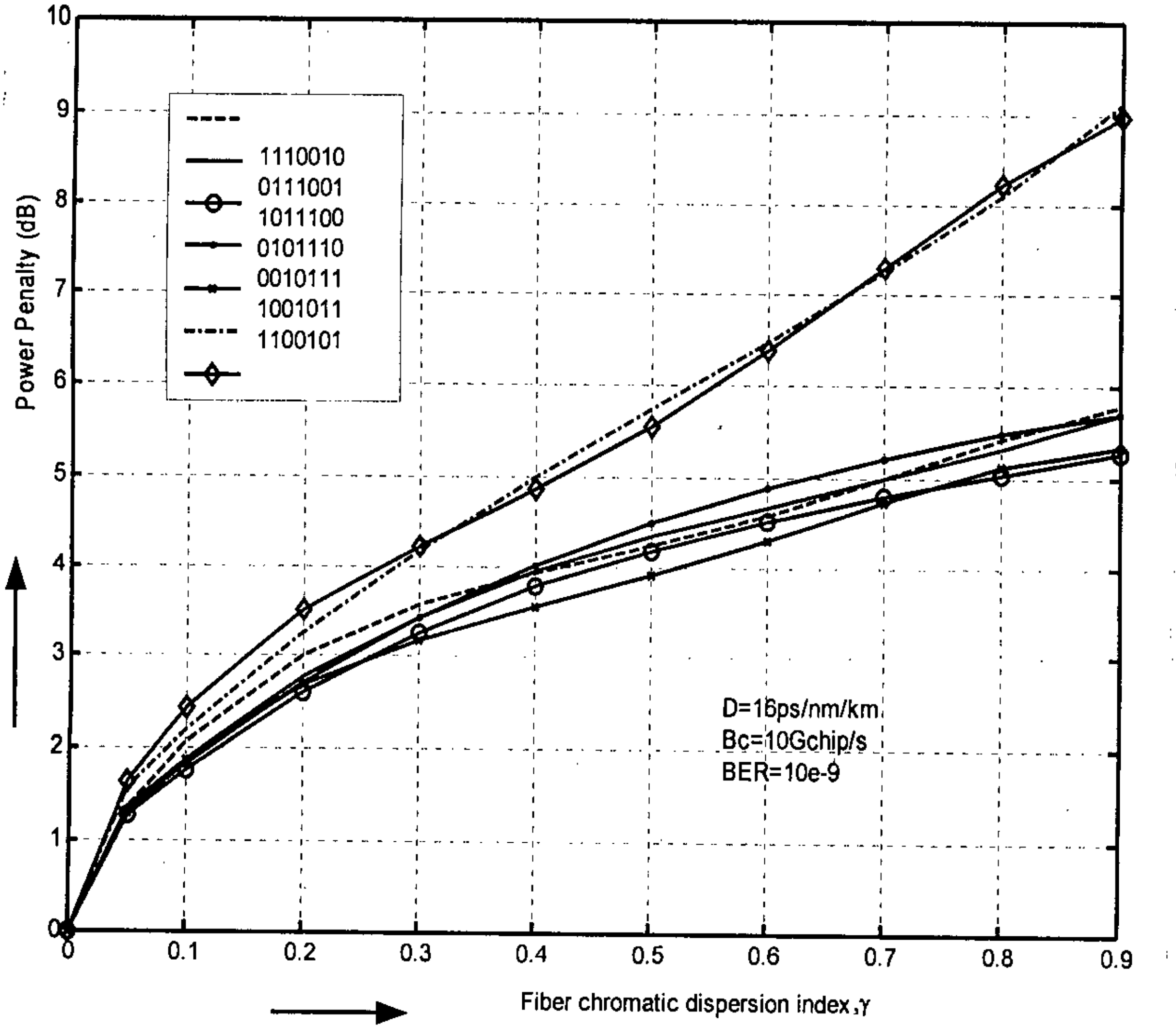

Fig. 3.15 Plots of penalty in signal power versus different values of fiber chromatic dispersion index, γ, for different type of 7 chip m-sequence pseudorandom code for a OCDMA DD-SIK receiver, at a chip rate Bc, 10Gchip/s with fiber chromatic dispersion, D=16ps/km-nm and bit error rate, BER= 10^{-9}. The reference sequence is 1110010 and other sequence is obtained by shifting 1 chip position

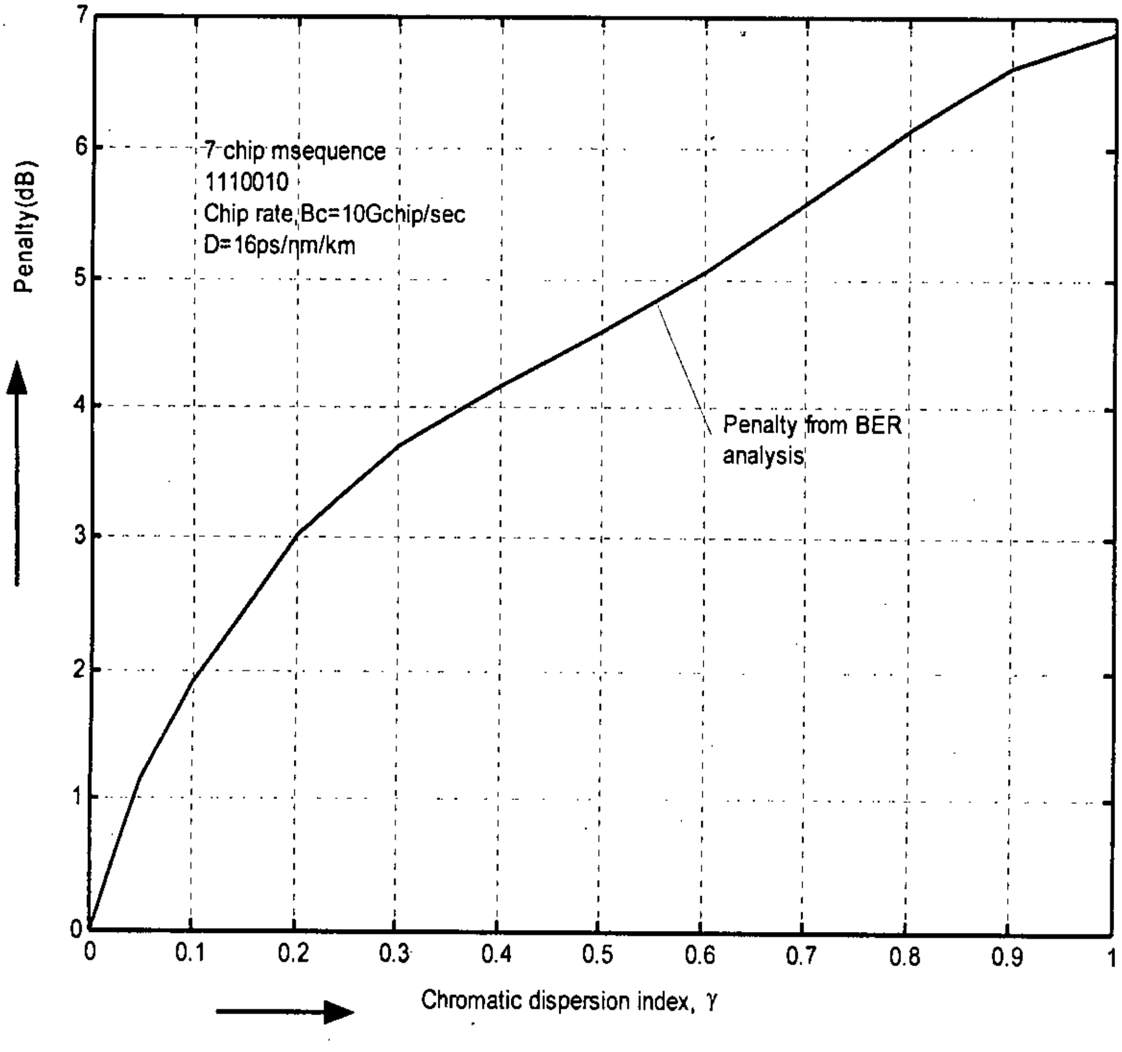

Fig. 3.16 The plot of average penalty of the seven, 7 chip m-sequence.in signal power versus fiber chromatic dispersion index, γ in a receiver using OCDMA where the reference chip sequence is 1110010 at a chip rate Bc=10Gchip/s with fiber chromatic dispersion, D=16ps/km-nm and bit error rate, BER= 10^{-9}.

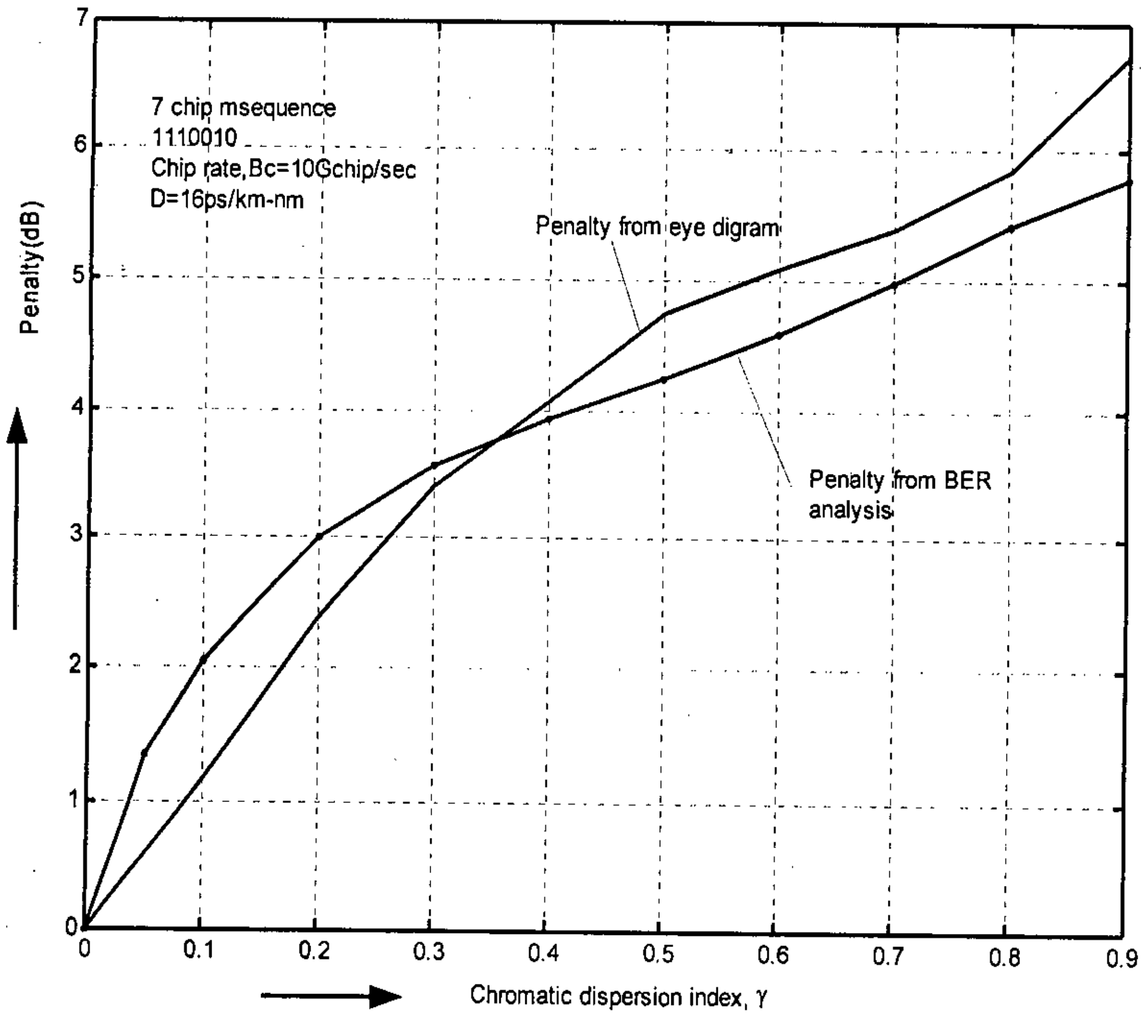

Fig. 3.17 The plots of the power penalty versus fiber chromatic dispersion index, γ of Fig. 3.16 and 3.7, those obtained from bit error rate performance and from eye diagram respectively, for 7 chip m-sequence, in an OCDMA transmission system with DD-SIK receiver where the reference chip sequence is 1110010, at a chip rate Bc=10Gchip/s with fiber chromatic dispersion, D=16ps/km-nm and bit error rate, BER= 10^{-9}.

than the other sequences due to the position of 1 on both side of these two sequences. So it is evident that power penalty depends on the change in position of 1 & 0 though the number of chip and number of '1's & '0's in all the seven sequences are same.

Fig. 3.16 depicts the plots of average of the plots of penalty of Fig. 3.15 versus the value of fiber chromatic dispersion.

Fig 3.17 shows the comparison between the plots of power penalty of Fig. 3.16 and Fig 3.7 obtained from bit error rate performance and from eye diagram respectively. The plot reveals that there is very little discrepancy in the values of power penalty evaluated from the bit error rate performance at BER=10^{-9} and that from the eye opening. The difference between the two estimated as less than 0.5dB which validates the approximation made in carrying out the theoretical analysis for bit error rate.

Fig. 3.18 depicts the plots of bit error rate versus received power, P_R (dBm) for varying number of simultaneous users, K for a 32 chip Gold sequence 00001010101111000010100001100001 with fiber chromatic dispersion index, γ=.3. Similar plots are depicted in Fig. 3.19 and Fig. 3.20 for γ = 0.5 and 1.0 respectively for the 32 chip gold sequence and Fig. 3.21, 3.22 and 3.23 for γ = 0.3, 0.5 and 1. respectively for a 7 chip gold sequence 1110010. It is observed that in order to maintain a considerable bit error rate, BER value of 10^{-9} the amount of transmitted signal power increases with increasing number of simultaneous user, K. Also as the number of simultaneous users increases, the plots tend to reduce in steepness reflecting that the rate of increase in BER with increased received power, speeds up. One interesting observation is that the separation between plots increases exponentially. It is further noticed that for a large number simultaneous user the bit error rate versus received power, P_R (dBm) may eventually results in a bit error rate floor which causes no further decrease in BER even the received power is increased. The bit error rate floor occurs at a higher value of BER at large values of K, due to multiuser interference (MUI).

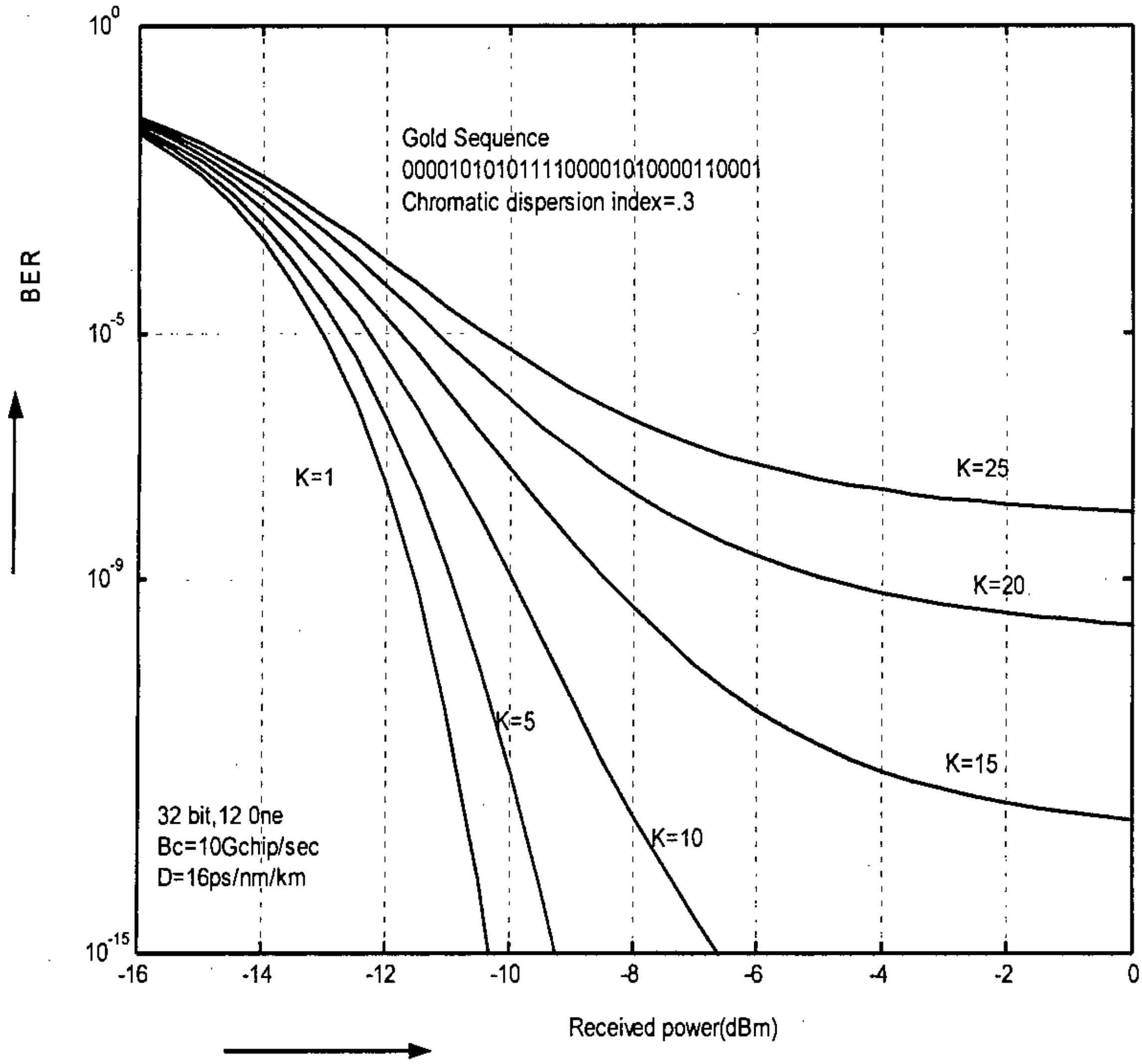

Fig. 3.18 The bit error rate (BER) performance of an optical CDMA transmission system with 32 chip Gold-sequence and DD-SIK receiver for different number of users at fiber chromatic dispersion index, γ=0.3. The chip sequence is 00001010101111000010100001100001, at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm .

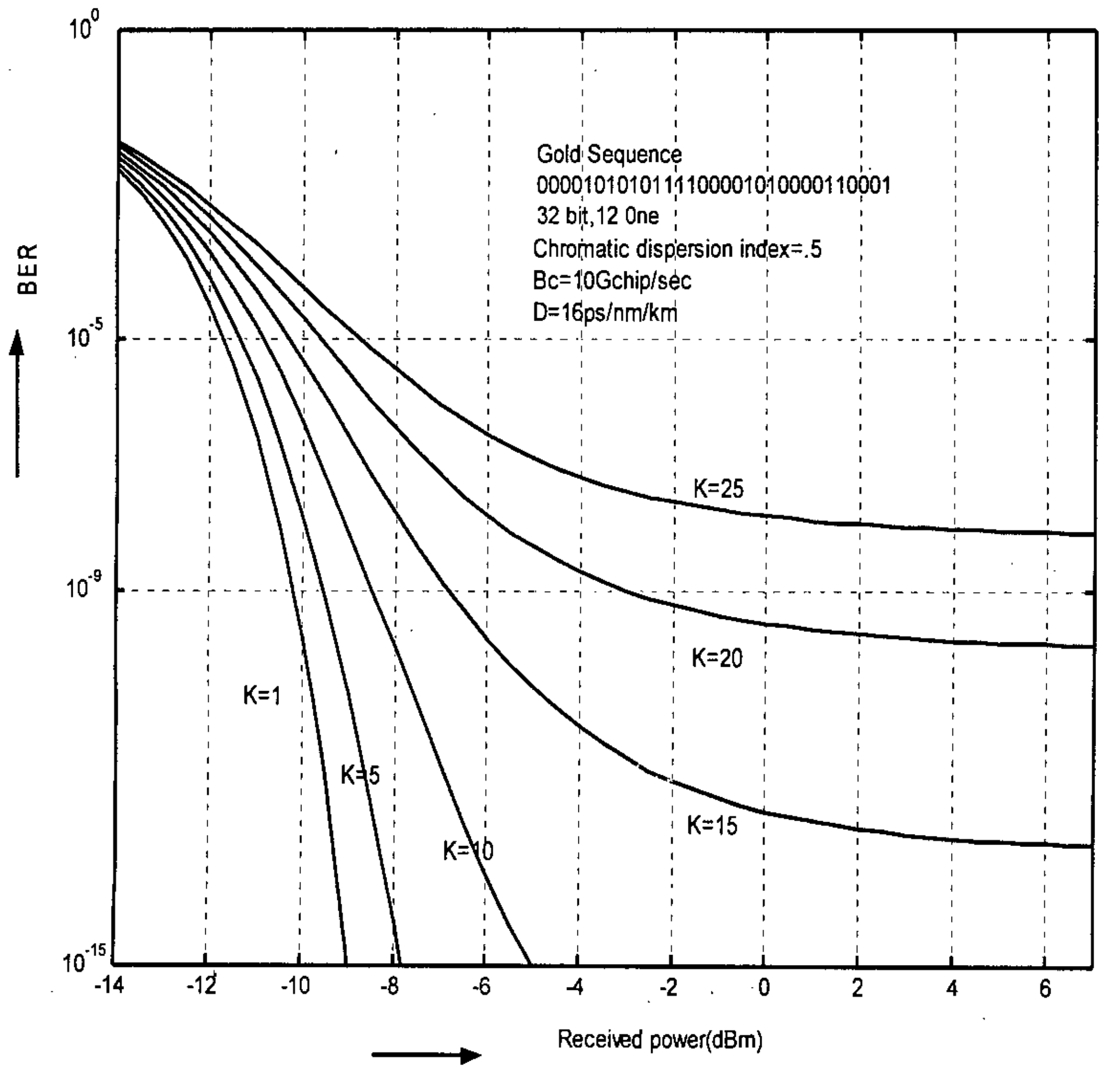

Fig. 3.19 The bit error rate (BER) performance of an optical CDMA transmission system with 32 chip Gold-sequence and DD-SIK receiver for different number of users at fiber chromatic dispersion index, γ=0.5. The chip sequence is 00001010101111000010100001100001, at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm .

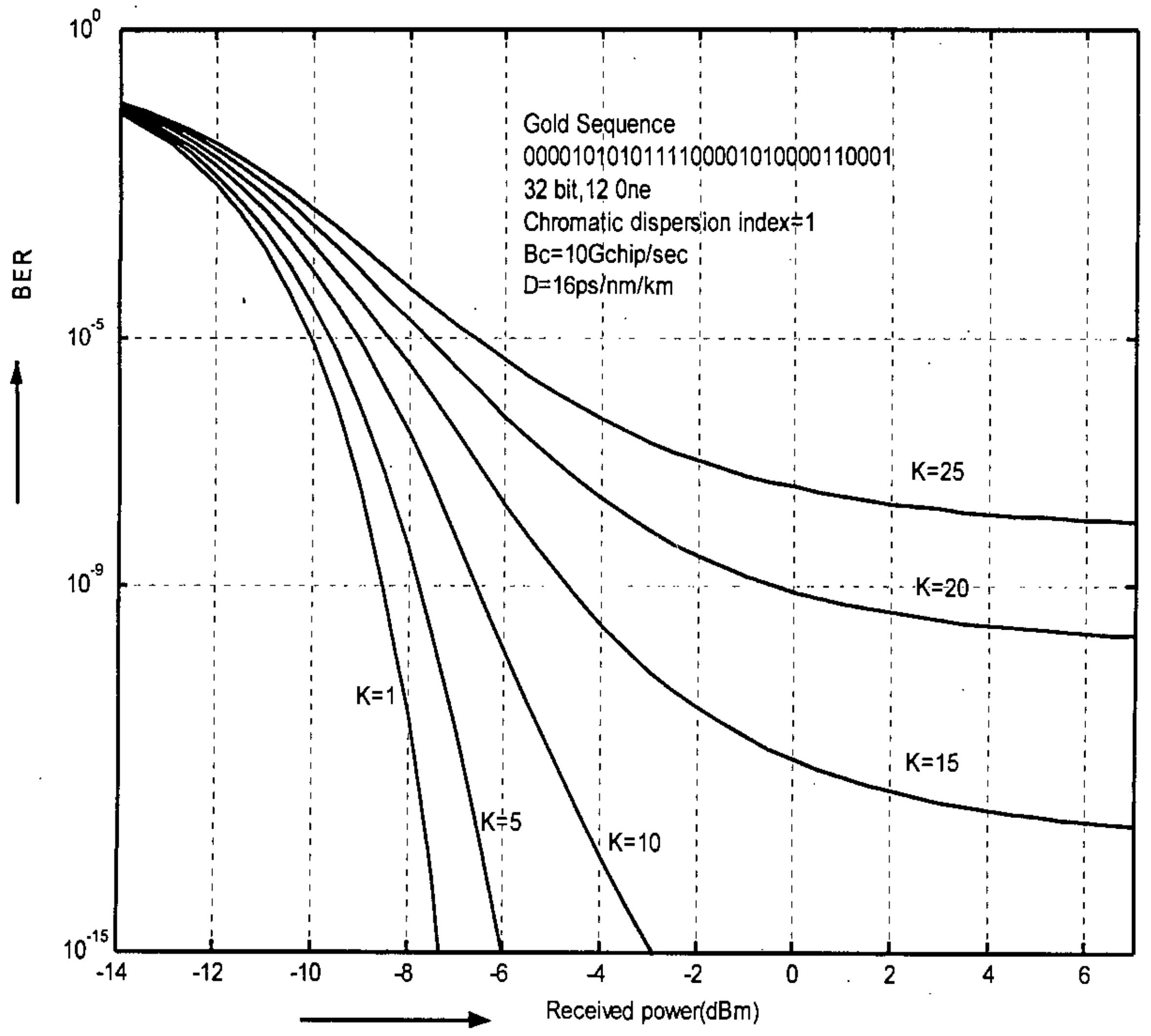

Fig. 3.20 The bit error rate (BER) performance of an optical CDMA transmission system with 32 chip Gold-sequence and DD-SIK receiver for different number of users at fiber chromatic dispersion index, γ=1.0. The chip sequence is 00001010101111000010100001100001, at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm .

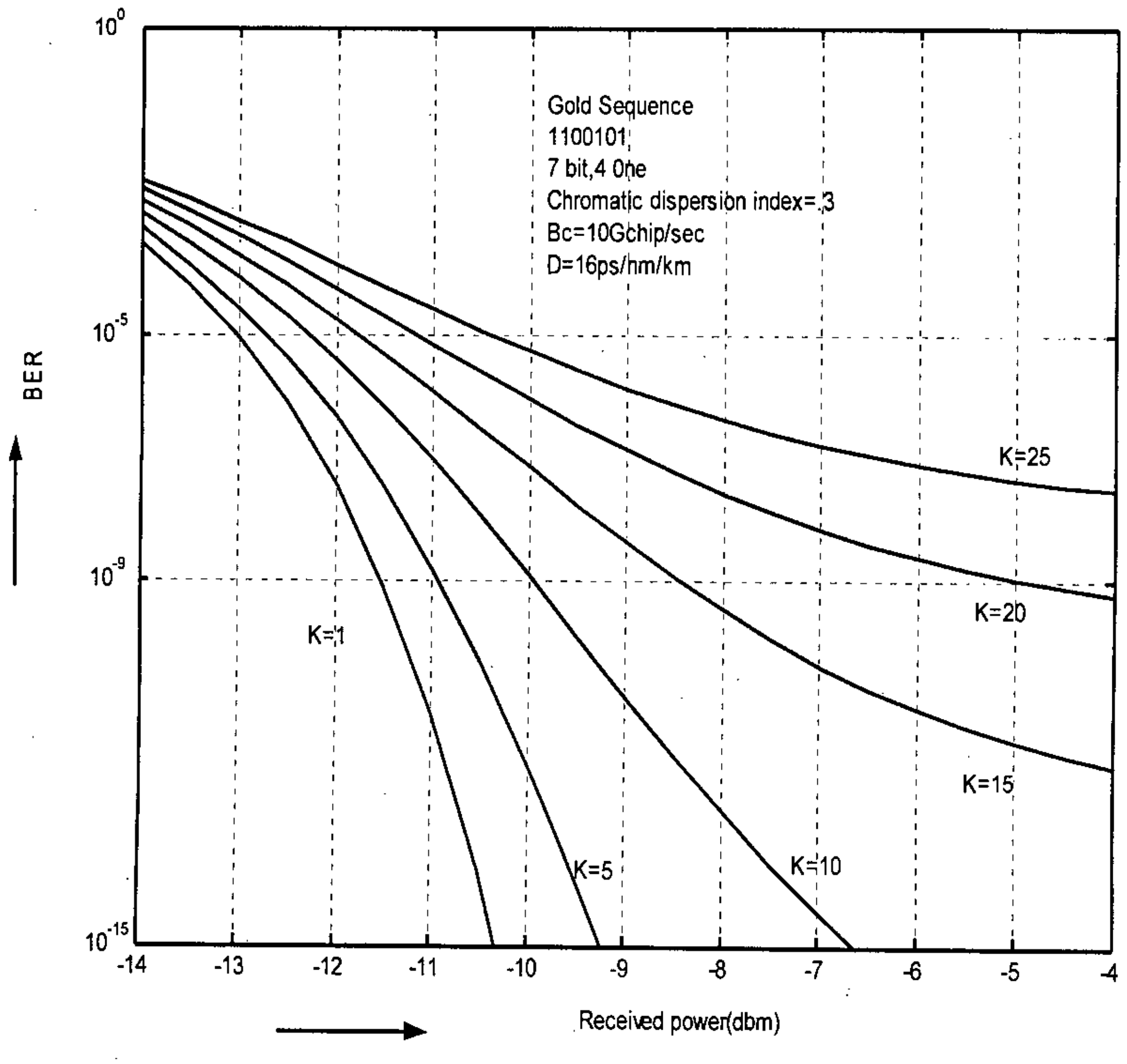

Fig. 3.21. The bit error rate (BER) performance of an optical CDMA transmission system with 7 chip Gold-sequence and DD-SIK receiver for different number of users at fiber chromatic dispersion index, γ=0.3 The chip sequence is 1100101, at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm .

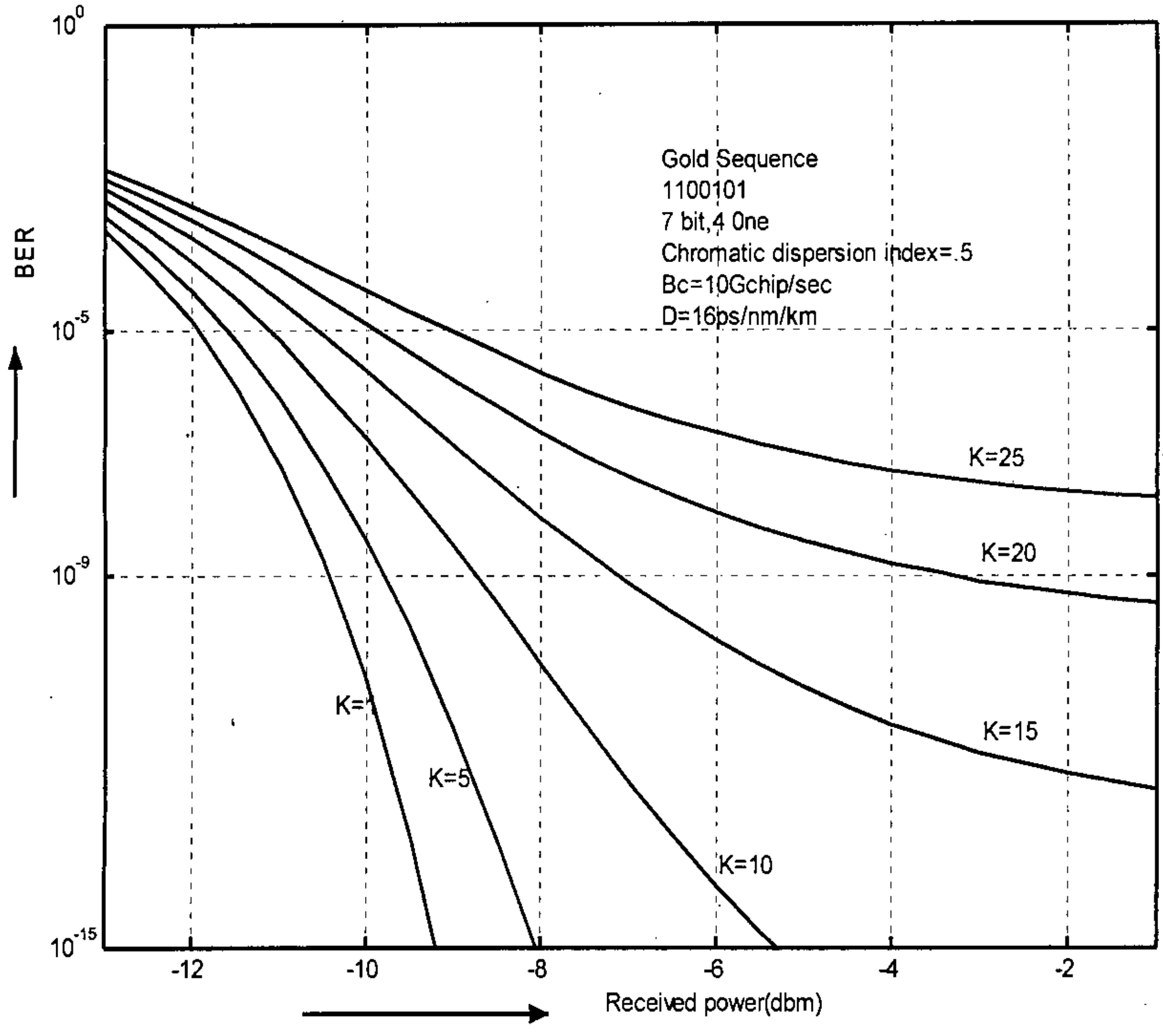

Fig 3.22. The bit error rate (BER) performance of an optical CDMA transmission system with 7 chip Gold-sequence and DD-SIK receiver for different number of users at fiber chromatic dispersion index, γ=0.5 The chip sequence is 1100101, at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm .

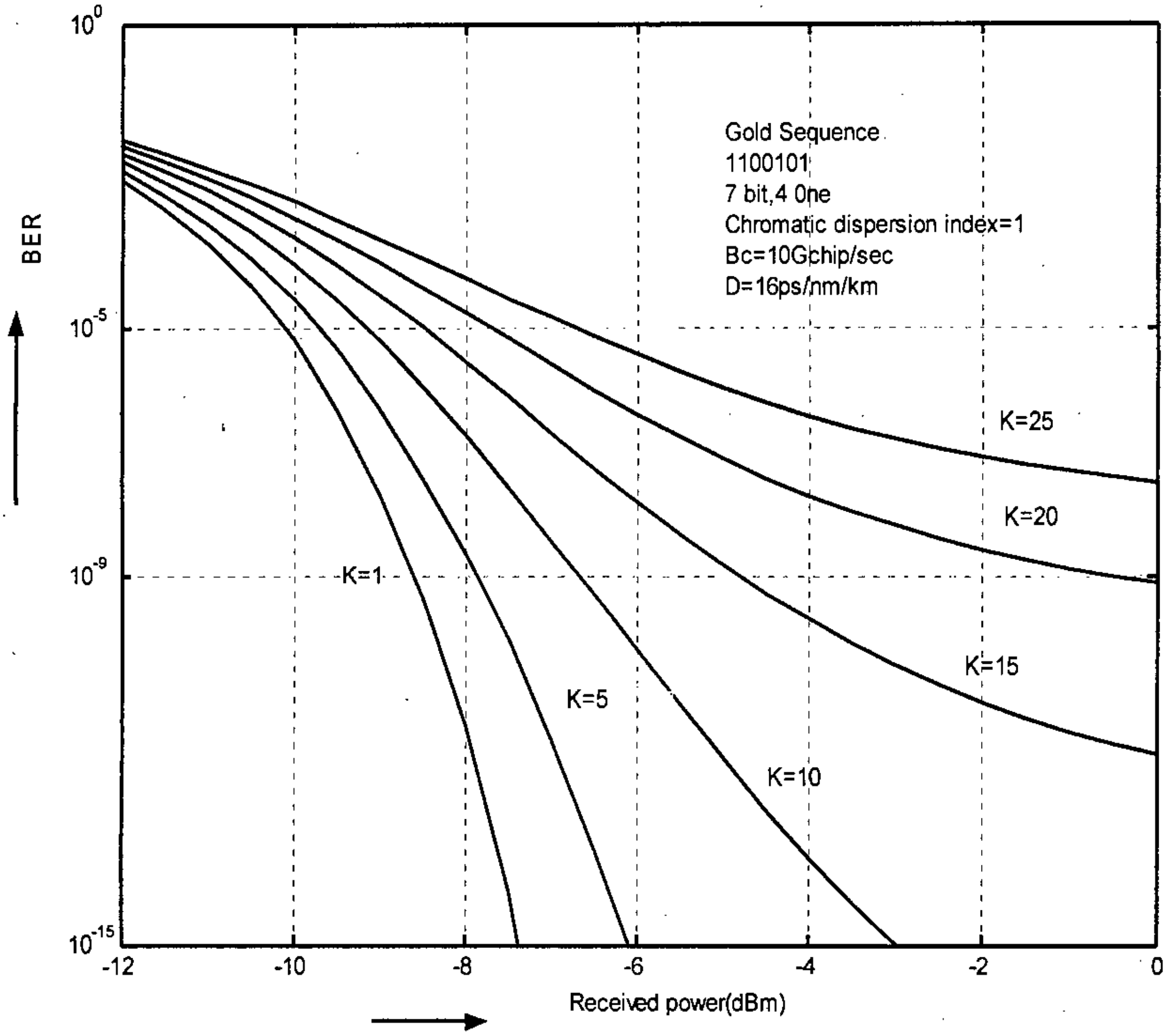

Fig 3.23. The bit error rate (BER) performance of an optical CDMA transmission system with 7 chip Gold-sequence and DD-SIK receiver for different number of users at fiber chromatic dispersion index, γ=1.0. The chip sequence is 1100101, at a chip rate Bc=10 Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm .

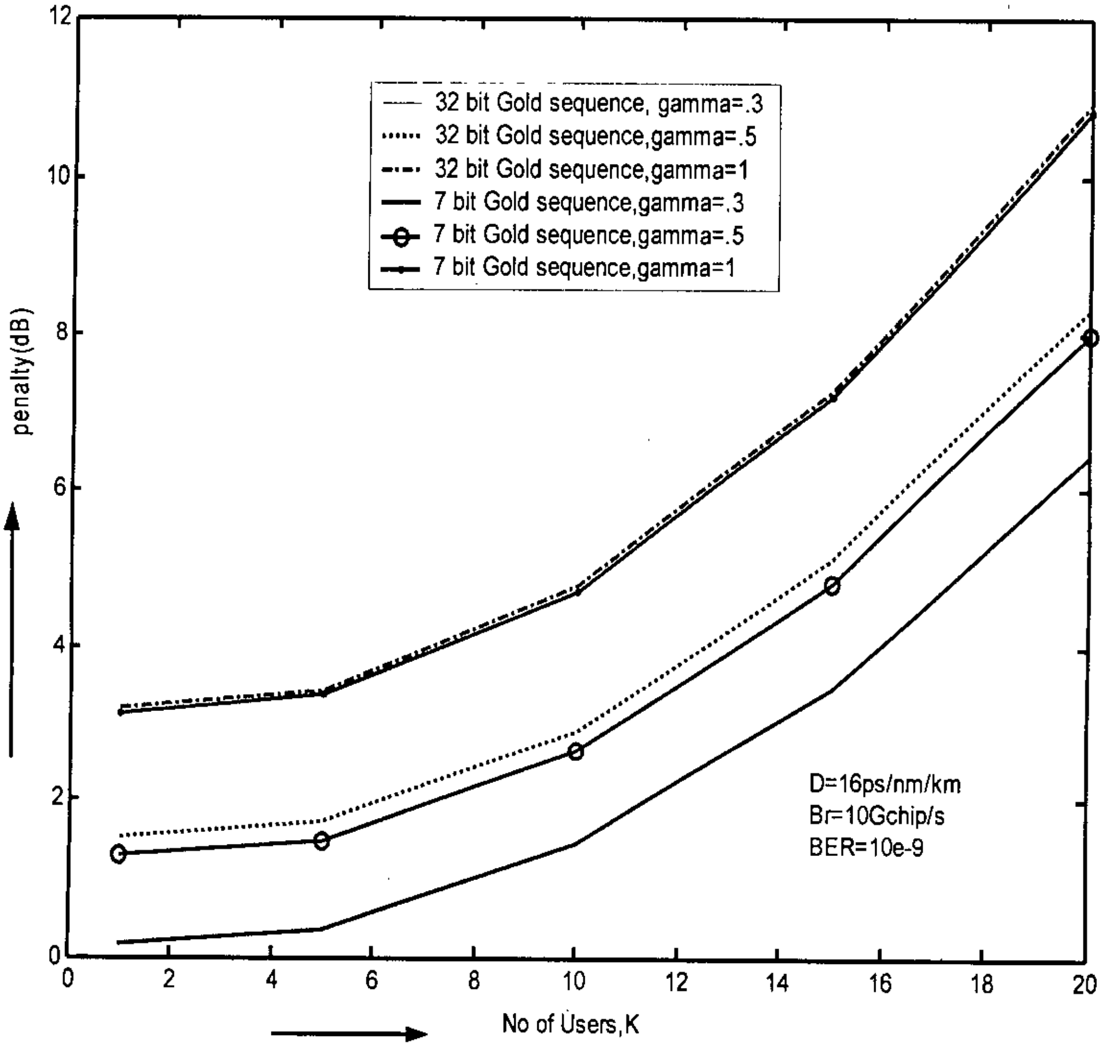

Fig. 3.24 Plots of penalty in signal power versus various number of users in an optical CDMA transmission system for different values of fiber chromatic dispersion index, γ, in case of 32 chip (00001010101111000010100001110001) and 7chip (1100101) gold sequence, respectively with DD-SIK receiver, at a chip rate Bc=10Gchip/s with fiber chromatic dispersion coefficient, D=16ps/km-nm and bit error rate, BER= 10^{-9}.

Fig 3.24 depicts the plots of power penalty versus nunber of simultaneous users for the seven chip gold sequence and 32 chip Gold sequence with the values of γ as 0.3, 0.5 and 1. The 32 chip gold sequence for γ=.3 is defined as base receiver sensitivity which is -11.5385dBm. the plots reveal that the system suffers a little bit higher penalty for 32 chips Gold sequence compared to 7 chips Gold sequence for a fixed value of γ and fixed number of users. The power penalty curves increase exponentially with the increase in simultaneous user for each case. It is observed that for a specific chip sequence and number of users the higher the value of γ, the higher is the value of power penalty. For example, for an allowable power penalty of 2 dB, the maximum allowable number of users is 11 for γ=0.3 and 6 for γ=0.5, for 32 chip Gold sequence. It is also evident that for a fixed power penalty the 32 chip Gold sequence can accumulate less number of users compared to 7 chip Gold sequence for a specified number of 1 & 0 and their position.

Chapter 4

Conclusions and Suggestions for future work

4.1 Conclusions:

A theoretical analysis is provided for a direct sequence optical code division multiple access (DS-OCDMA) transmission link with an intensity modulated direct detection (IM/DD) sequence inversed keyed (SIK) optical correlator receiver. The analysis is carried out to evaluate the effect of fiber chromatic dispersion on the system performance and then the expression for bit error rate probability is developed.

Following the theoretical analysis the bit error rate performance results are evaluated at a chip rate of 10Gchip/s with single mode fiber at a wavelength of 1550 nm, fiber chromatic dispersion coefficient 16ps/nm/km, for different sets of values of fiber chromatic dispersion index, different types and length of code sequence and multiple access interference (MAI) in the presence of receiver thermal and shot noise .

The results show that the performance of a SIK receiver for DS-CDMA transmission link degrades due to the fiber chromatic dispersion which is evident from both the eye diagram and the bit error rate performance analysis. Even for small values of dispersion index,γ the system suffers penalty at a specified bit error rate of 10^{-9} compared to the case of without dispersion and becomes very much significant at higher values of chromatic dispersion index. For example, at a chip rate of 10Gchip/s, D=16ps/nm/km and for a specified seven chip m-sequence, the penalty suffered by the system to maintain a BER 10^{-9}, is 2.05dB, 4.25dB, 5.78dB for γ=.1, γ =.5 and γ=.9 respectively, obtained from the BER performance analysis. For the same system parameters, the penalty obtained from the eye diagram is 1.19dB, 4.74dB and 6.74dB for γ=.1, γ =.5 and γ=.9 respectively. The difference of penalty obtained from the two methods is less than 0.5 dB which validates the approximation made in carrying out the theoretical analysis for bit error rate.

The system also experiences variation in power penalty with different types and length of code sequence. For example, at a chip rate of 10Gchip/s, D=16ps/nm/km, γ=.5, the required power penalty is 1.28 and 1.5 for 7 chip m-sequence and 32 chip Gold sequence respectively. It is also investigated, that keeping all the system parameters unchanged, the system suffers variation in penalty with the change in position of '1' and '0', in spite of same number of '1's and '0's in a chip sequence. For example, when γ=.9, the system suffers, for specified values of parameters, a power penalty of 5.32dB for the 7 chip m-sequence, 1011100 and that of 9.12dB for the 7 chip m-sequence 1001011. This discrepancy is due to the fact that in later one there situates '1's both at the beginning and at the end of the sequence which are half eliminated at the two edges during simulation.

The power penalty for the DS-CDMA SIK receiver increases with the increase in number of simultaneous user for a specific value of system parameters. For example, For a 32 bit Gold sequence and γ=.3, the system suffers a penalty of .35dB for 5 simultaneous users and 6.43dB for 20 simultaneous users, due to multiple access interference, at a chip rate of 10Gchip/s, D=16ps/nm/km. It is also observed that the system can serve more users for a fixed penalty at a lower value of fiber chromatic dispersion index, γ.

4.2 Suggestions for future work:

Future research related to this work can be carried out to investigate the influence of fiber chromatic dispersion in a Frequency hopped (FH) optical CDMA system using FH encoder and decoder.

Further research in this area can also be carried out to investigate the system performance for various types of code sequences with different length and thereby select the suitable sequences for minimum power penalty.

Further research related work can be carried out to reduce the effect of multiple access interference (MAI) which will increase the number of simultaneous users by placing an optical hard limiter at the front of the DS-CDMA SIK receiver.

Further works of importance are to determine the impact of fiber nonlinear effect such as self phase modulation (SPM) and cross phase modulation (XPM) on the performance of a direct sequence spread spectrum IM/DD transmission system using SIK correlator receiver.

Further research work can be carried out to evaluate the effect of crosstalk in the presence of four wave mixing (FWM) effect in an optical CDMA system with direct detection IM/DD SIK correlator receiver.

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