# Department of Electrical and Computer Systems Engineering

## Technical Report
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Multi-level Linecoding for Ultra-high Speed Long-haul Optical Fibre Communications Systems

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# MULTI-LEVEL LINE CODING FOR ULTRA-HIGH SPEED LONG HAUL OPTICAL FIBRE COMMUNICATION SYSTEMS

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## ABSTRACT

*The demands for greater spectral efficiency, higher line rate, higher channel count, greater amplifier/repeater spacing, Tb/s capacity DWDM long haul optical communication systems, efficient transmission of optical channels over long-haul optical fibre system is essential. Since the conventional Return to zero (RZ) and Non return to zero (NRZ) modulation formats suffer from dispersion and inefficient for multiplexing several channels, multi-level signaling using novel modulation formats, such as novel optical coding and carrier suppressed – duo-binary are studied in this paper for Tb/s capacity optical transmission systems.*

*A comprehensive modeling platform is demonstrated and the modulation formats are described in detail. Performances of these modulation formats are analyzed against impairment factors such as fiber dispersion, fiber non linear effects, and optical power loss. We demonstrate that, novel optical coding can be used to transmit 65 x 40Gbps channels, while 81 x 40Gpbs DWDM channels can be transmitted using carrier suppressed duo binary modulation, along 100km dispersion compensated optical fibre link. The achieved spectrum efficiency for these techniques is 0.41bit/s/Hz and 0.8bit/s/Hz respectively.*

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1. INTRODUCTION

Internet traffic, driven by multitude of new users and bandwidth – hungry applications, is rapidly surpassing all other forms of voice and data transfer within today's communication networks. Over the past few years, the capacity of optical transmission systems has been doubling[10]. The increase in the number of channels through dense wavelength division multiplexing (DWDM), accounts for most of this evaluation. However in order to achieve even higher capacities, the channel bit rates have to be increased, e.g. 40Gb/s in commercial products, the channel spacing must be reduced and the total exploited optical bandwidth has to be enlarged, and the total exploited optical bandwidth has to be enlarged. All three factors should be investigated simultaneously to realize higher spectral efficiency and greater total throughput.

Enabling technologies for high capacity (Tb/s), point to point, long distance transmission are (i) Low – noise, high – power, wide bandwidth and gain flattened optical amplifiers;(ii) Optimized optical fiber and associated dispersion management techniques for future – proof infrastructure and transmission, which is tolerant to propagation effects (iii) Optimized line coding techniques and modulation formats for high spectral efficiency; (iv) High-speed electronics and opto – electronics for the transmitter and receiver equipment;(v) Polarization mode dispersion (PMD) mitigation(vi) Dispersion compensating modules compatible with large optical bandwidths(vii) Fast optical processing for 2R – 3R regeneration providing efficient but lower cost regeneration compared with "back – to – back" transmit/receive equipment(viii) Very high bit rate equipment (60Gbps and beyond), based on combination of electronic time division multiplexing (ETDM), and optical time division multiplexing (TDM)

techniques; (ix) New generation of forward error correction techniques to facilitate noise tolerant transmission (x) Optical filters with well defined amplitude and phase shapes for ultra – narrow (narrower than the WDM channel bandwidth) filtering:

Among recent advances in the field of ultrahigh capacity transmission and ultra high bit rate components are a record terrestrial Terabits per second transmission systems with high spectral efficiency, which has never been achieved before, and the recent progress in the field of 40Gbps opto electronics and electronics components, showing that a new generation of components is feasible for the practical implementation of 40Gbps transmission systems.

Several developments are necessary to achieve a transmission rate of 40Gbps per channel. Opto-electronic devices and very fast integrated circuits are now available, although their high-speed capabilities often remain far from what is required. Lithium niobate external modulators are currently the lowest bandwidth components with in the transmitter. Moreover they require high drive voltage of more than $5V_{pp}$ to achieve high extinction ratio. Higher bandwidths and lower driving voltages can be achieved with the more compact InP based electro absorption modulators (EAM). InGaAs PIN photodiodes offer very large bandwidths and high responsivities. In addition, they can withstand high optical input powers and often exhibits very low sensitivities.

In addition to above, line coding is a vital factor in optical transmission. The performance limited by chromatic dispersion of optical transmission depends on the bandwidth of the optical signal. Line coding fits the spectrum of the data signal to the transmission channel characteristics. In conventional standard fiber transmission lines, the return to zero and non return to zero formats are the two modulation formats most often used. But when considering the factors such as spectral efficiency, power margin, tolerance against group velocity

dispersion and fiber non linearity effects like self phase modulation and cross phase modulation network designers has to chose alternative modulation formats such as carrier suppressed return to zero, novel optical coding, carrier suppressed duo binary at 40Gbps transmission rate.

Thus the principal objectives of this paper are: (i) Modeling the novel optical coding and carrier suppressed duo binary modulation formats in MAT LAB version 6.1 platform (ii) Simulating the 40Gbps per channel optical communication system and investigating the transmission performance of the system when using novel optical coding and carrier suppressed duo binary modulation techniques with external modulator.(iii) Investigating the performance of these modulation formats against the impairment factors such as fiber dispersion, fiber non linear effects, and optical power loss.(iv) Simulating Tb/s capacity, dispersion managed long haul DWDM optical communication system using multi level modulation techniques.

Line coding can be used to reduce the bandwidth of the signal to abate the signal distortion by chromatic dispersion. Partial response coding is a mode of line coding that can be realized by finite impulse response (FIR) filtering. The partial response signal is encoded into pseudo multilevel signal with the same data rate. Duo-binary coding is a simple partial response code implying low pass filtering of the signal. By using a chirp-free Mach-Zehnder modulator, the signal is AM-PSK modulated. The receiver can be a conventional binary direct detecting receiver.

The other common line coding technique use multilevel signaling is the novel optical line code. Duobinay is a special case of order one novel optical line code, and the latter use four

levels instead of the three levels of duo binary. In this paper work, the use of these multilevel modulation formats in Tb/s transmission rates is discussed in detail.

In this paper the performance of order one novel optical line code and duo-binary coding, in highly dispersive fiber is compared with the conventional return to zero (RZ) and non return to zero (NRZ) line coding techniques. Dispersion compensation techniques and non-linear tolerance is discussed for the interested coding techniques. Finally multi channel transmission using DWDM technique along a dispersion compensated fiber optic link is illustrated.

The report is organized as follows. In section two, line-coding techniques are introduced with a special attention to the novel optical line coding and duo-binary line coding. Analytical methods used to develop software coding are also discussed in detail.

Section three describes the optical transmitters and modulation characteristics of light sources and biasing management of Mach Zehnder modulators for multilevel modulation. Factors to be considered for the design of optical fiber communication system are illustrated in section four. Section five gives the performance comparison of RZ, NRZ and multi-level optical coding and carrier suppressed duo binary modulation technique. Finally concluding remarks of the paper are given.

## 2. LINE CODING TECHNIQUES

### 2.1    An introduction to line coding for optical communication systems

The rapid worldwide growing of data and Internet traffic in telecommunication networks results in a sharp increase in the demand for transmission capacity. Thus more efficient utilization of the existing optical fiber network is an answer that meets economical

constraints. An important step is an introduction of optical communication systems with terabits per second capacity, which are based on DWDM technology. Thus for the first time bandwidth efficiency, which is an important feature in wireless communication has become an important issue in fiber optics.

There are several approaches to achieve overall bandwidth efficiency. Amongst them are improved modulation format, line-coding techniques, management of chromatic and polarization mode dispersion including equalization, wideband optical amplifiers, improved WDM multiplexes and demultiplexes. Modeling of the WDM optical channel including nonlinear effects is necessary in order to investigate the impact of the various methods. For practical reasons it is important (to avoid high complexity algorithms) to end up with structures that are realizable at these high frequencies.

Therefore research engineers focus mainly on bandwidth efficient modulation formats at channel data rates 40Gbps. By saving bandwidth both the dispersion problems and the channel density are improved. A promising approach is multilevel signal line coding.

The popular line coding formats such as RZ and NRZ are worked well up to 10Gbps per channel long haul high-speed optical communication networks. Recent analysis and investigations have shown that RZ turned out to be superior compared to conventional NRZ systems, at least as long as standard single mode fibers are used as transmission media. The RZ format has been reported to be effective against self phase modulation (SPM) in standard single mode fiber links. [4] SPM resulting from fiber non-linearities caused by group velocity dispersion (GVD) leads to waveform distortion that limits the maximum transmission distance and capacity of high-speed optical links. Thus tolerance with respect to both SPM and GVD are essential for reliable network operation. On the other hand, because of the

narrower optical spectrum of NRZ format, NRZ enables higher spectral efficiency in wavelength division multiplexing (WDM) systems compared to RZ in the linear region. [3] However the tolerable dispersion range is limited in both RZ and NRZ modulation formats. In addition, they limit the potential distance of the signal due to the non-linearity effects of fiber, when they are used in terabit capacity optical communication networks.
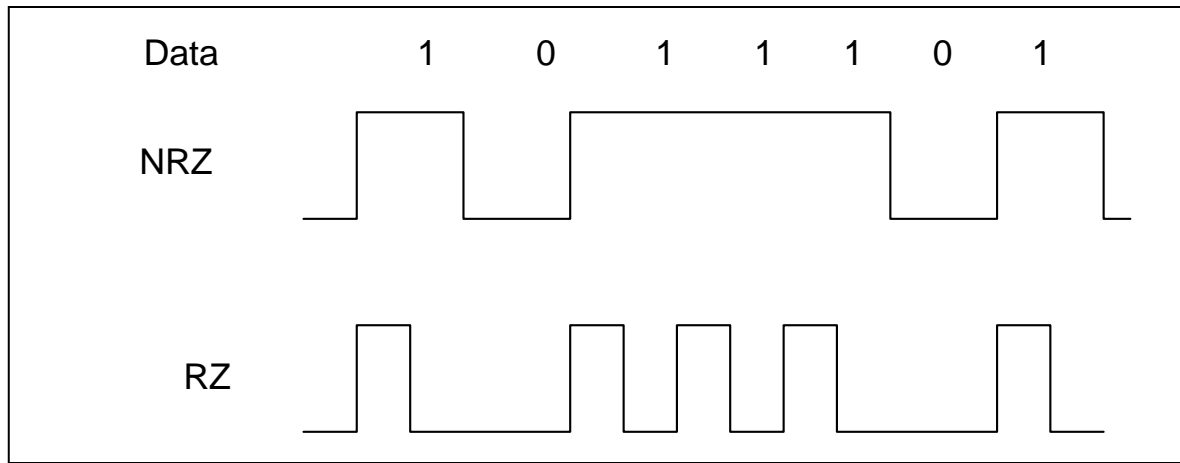


*Figure 1*: Coding formats of NRZ and RZ

In MOCSS, the carrier suppressed return to zero (CSRZ) modulation format has been used to simulate 40Gbps optical communication systems since it offers large power margin in dispersion managed transmission lines using single mode fiber (SMF) at a line rate of 40Gbps.

In this section generation of multilevel coding formats such as novel optical coding and carrier suppressed duo-binary is discussed in detail. In Section 2.2 a description of novel optical coding is provided with the method of generation, while in Section 2.3 analytical method used to generate duo binary coding is discussed.

## 2.2    A multi-level novel optical line code

Novel optical line coding is similar to conventional miller coding with the difference being that two of them are scaled by a factor $\alpha < 1$ and transmitted in sequence according to the duobinary logic. Novel optical codes are ranging from order 1, 2 ….n and in MOCSS only order one novel optical codes are used.

### 2.2.1   First order code

The first order code uses four wave forms $s_i(t)$, and the state diagram is shown in the Figure 2,  where $\Sigma_1$, $\Sigma_2$ are the code status and the elementary signals $s_i(t)$, where $I = 1,2,3,4$ are depicted.
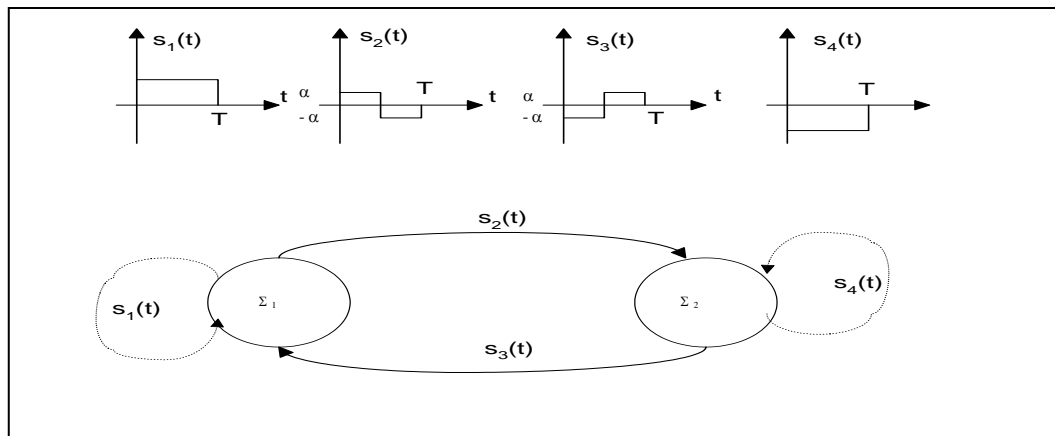


*Figure 2*:Elementary signals and coding state diagram for novel  multi-level optical line code

of order one [5]

Elementary signals form two pairs with $s_1(t) = - s_4(t)$ and  $s_2(t) = - s_3(t)$. In addition two of the elementary signals *[$s_2(t)$ and $s_3(t)$]* are scaled by $\alpha$. In MOCSS $\alpha$ is chosen as 0.5 to produce best spectral shape.

The information (data) sequence $\{U_k\}$ is encoded to form the coded signal.

$$x_e(t) = \sum_{k=-\infty}^{\infty} g_k(\sigma_k) s_e(t - kT; u_k) \tag{1}$$

where $\sigma_k$ denotes the generic encoder state and $g_1(\sigma_k)$ is a coefficient defined by the following rule

$$g_1(t, u_k) = \begin{cases} 1, \dots s_1(t)..if.\sigma_k = \Sigma_1 \\ -1, \dots s_2(t)..if.\sigma_k = \Sigma_2 \end{cases} \tag{2}$$

where $\Sigma_1$ and $\Sigma_1$ indicates the states allowed to the encoder, and $s_e(t;u_k)$ is one of the two elementary signals $s_1(t)$ or $s_2(t)$ selected in accordance with the following rule.[5]

$$s_e(t, u_k) = \begin{cases} s_1(t)..if.u_k = 0 \\ s_2(t)..if.u_k = 1 \end{cases} \tag{3}$$

Hence the actual elementary signal output from the encoder will be one of $s_1(t)$, $s_2(t)$, $s_3(t)$, $s_4(t)$. The sequence of the states of the encoder is defined by the following rule.

$$\sigma_k + 1 = g_2(u_k, \sigma_k) \tag{4}$$

The above encoding rules are summarized in Table 1.

| Information Sequence($u_k$) | Generic encoder state ($\sigma_k$) | Sequence of the state of the encoder ($g_2$) | Encoded signal $x_e(t)$ |
|---|---|---|---|
| 0 | $\Sigma_1$ | $\Sigma_1$ | $s_1(t)$ |
| 0 | $\Sigma_2$ | $\Sigma_2$ | $-s_1(t) = s_4(t)$ |
| 1 | $\Sigma_1$ | $\Sigma_2$ | $s_2(t)$ |
| 1 | $\Sigma_2$ | $\Sigma_1$ | $-s_2(t) = s_3(t)$ |

*Table 1: Summary of the encoding criteria for novel optical code*

An example of a waveform generated by the order one code with $\propto = 0.5$ is shown in the *Figure 3*.
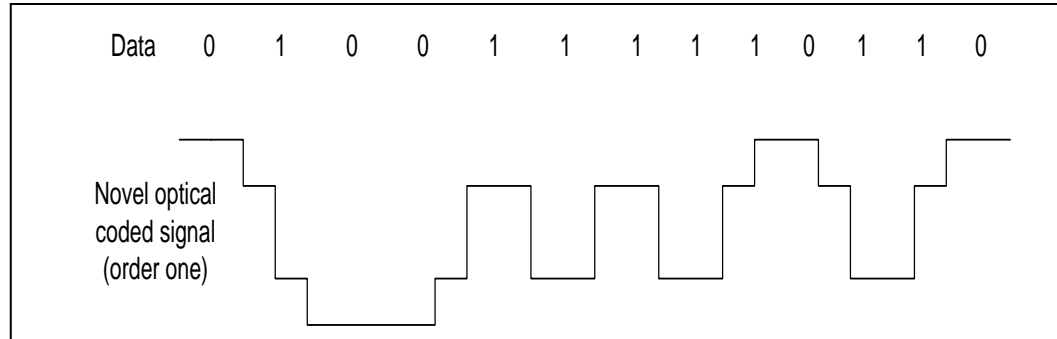


Figure 3: novel optical coded signal

2.2.2    Novel optical line code generation

Elementary signals of order one code can be generated by expressing four elementary signals of figure 2 as linear combinations of the rectangular pulses of duration *T/2*.

$$p(t) = \begin{cases} 1, 0 < t < T/2 \\ -1,..0....elsewhere \end{cases} \tag{5}$$

Therefore, the elementary signals can be defined as : $s_1(t) = p(t) + p(t - T/2)$; $s_2(t) = 0.5[p(t) - p(t - T/2)]$; $s_3(t) = -s_2(t)$; $s_4(t) = -s_1(t)$ with *T* is the bit period of the data sequence. In Matlab codes p(t) is defined as $p(t) = [1 - exp(-t/t_{rise})^2]$ and p(t-T/2) is defined as $p(t - T/2) = [exp(-t/t_{rise})^2$.with $t_{rise}$ is the circuit rise time. Circuit rise time determines the 3dB modulation band width. The four basic factors that limit the system speed are the transmitter rise time, the material and modal dispersion rise time of the fiber transmission link, and the receiver rise time. In MOCSS modulation bandwidth of the external modulator is taken as 30GHz and the rise time of novel optical order one code is

$$t_{rise} = \frac{0.0001}{Modulationbandwidth} \tag{6}$$

Figure 4 shows the novel optical coded (order one) signal obtained from MOCSS software package and its power spectrum calculated from the discrete Fourier transform of the modulating voltage waveform as

$$P_n(e^{j\varpi}) = \frac{1}{N} | I_m(e^{j\varpi}) |^2 \tag{7}$$

Where $I_m(e^{j\omega})$ is the modulating signal in the frequency domain and $N$ is the number of samples in a sequence of discreet time waveforms
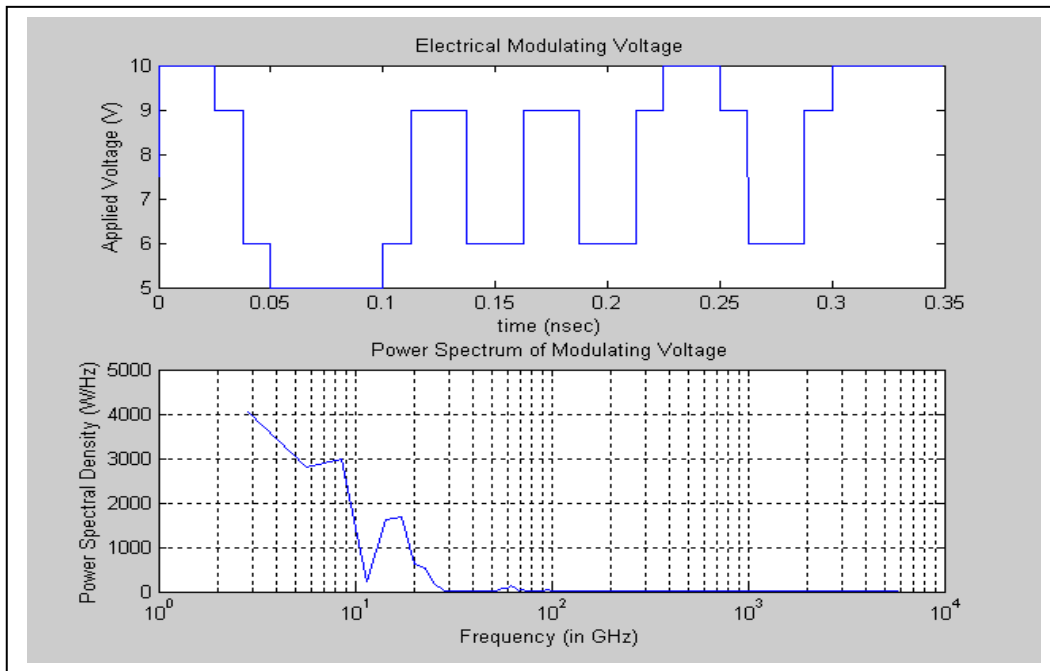


Figure 4: Novel optical coded electrical modulating signal of '*0 1 0 0 1 1 1 1 1 0 1 1 0*' and its power spectrum (from MOCSS)

2.3     Optical Duo-binary coding

The duo binary coding format is intended to increase the data transmission is intended to increase the data transmission efficiency by means of coding. According to A. Lender who discovered the concept of correlative transmission techniques, duo means doubling the binary capacity by bandwidth compression. It takes the advantage of all the three possible amplitude levels: the mark state is represented by the zero (or center) level; the space state is represented by either by a positive (or top) or a negative (or bottom) level. This scheme assures that the only permitted transitions in successive bits are between any two adjacent symbols. These patterns follow the unique rule; the polarities of two successive bits at the extreme levels are opposite.
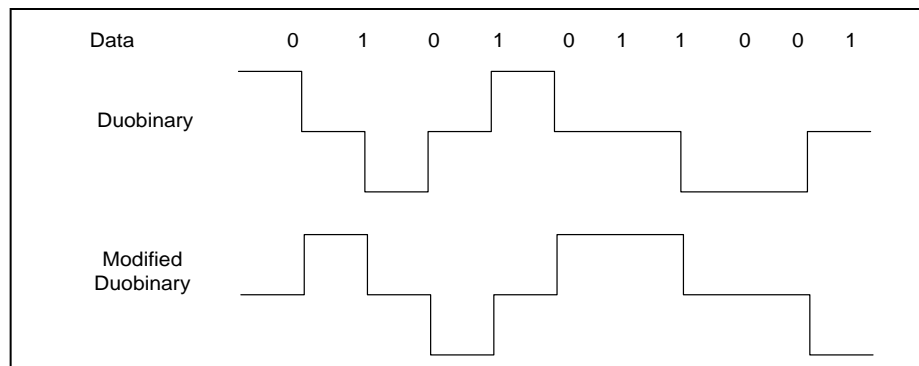


*Figure 5* Duo-binary coded signal and modified duo binary coded signal

The modified duo binary is another partial response signaling (PRS) scheme that involves a correlation span of two digits. It is a DC free format and also has three levels. The pulse train is divided odd and even bits. Both odd and even pulse trains follow the same rule: two successive bits at the extreme levels always have opposite polarity [6]. Contrary to duo binary case transition from top level to the bottom one or vice versa can occur. As a consequence, the width of the eye pattern diagram is narrower, which indicates an increase

inter symbol interference (ISI). As well as duo binary modified duo binary allows a 2:1 bandwidth compression.

The duo binary line code can be generated with three elementary signals shown in Figure 6.
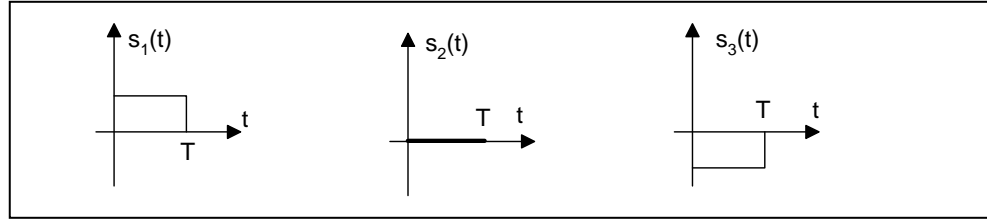


*Figure 6*: Elementary signal for duo binary line code

Elementary signals $s_1(t)$ and $s_3(t)$ can be expressed as a linear combination of rectangular pulses of duration $T/2$

$$p(t) = \begin{cases} 1, 0 < t < T/2 \\ -1, ..0....elsewhere \end{cases} \tag{8}$$

Then the $s_1(t)$ and $s_3(t)$ can be expressed as $s_1(t) = p(t) + p(t - T/2)$, $s_3(t) = -s_1(t)$ and $s_2(t) = 0$ where $T$ is the bit period of the data sequence.

In Matlab codes p(t) is defined as $p(t) = [1 - exp(-t/t_{rise})^2]$ and $p(t-T/2)$ is defined as $p(t - T/2) = [exp(-t/t_{rise})^2]$ with $t_{rise}$ is the circuit rise time. For duo binary coding $t_{rise}$ is taken as,

$$t_{rise} = \frac{0.0001}{Modulation..bandwidth}$$

$$x_e(t) = \sum_{k=-\infty}^{\infty} g_k(\sigma_k) s_e(t - kT; u_k) \tag{9}$$

The information (data) sequence $\{U_k\}$ is encoded to form the coded signal with $\sigma_k$ denotes the generic encoder state and $g_1(\sigma_k)$ is a coefficient defined by the following rule

$$g_1(t,u_k) = \begin{cases} 1,...s_1(t)..if.\sigma_k = \Sigma_1 \\ -1,...s_2(t)..if.\sigma_k = \Sigma_2 \end{cases} \tag{10}$$

where $\Sigma_1$ and $\Sigma_2$ indicate the states allowed to the encoder, and $s_e(t;u_k)$ is one of the two elementary signals $s_1(t)$ or $s_2(t)$ selected in accordance with the following rule[5]

$$s_e(t,u_k) = \begin{cases} s_1(t)..if.u_k = 0 \\ s_2(t)..if.u_k = 1 \end{cases} \tag{11}$$

Hence the actual elementary signal output from the encoder will be one of $s_1(t)$, $s_2(t)$, $s_3(t)$. The sequence of the states of the encoder is defined by $\sigma_k + 1 = g_2(u_k, \sigma_k)$. The above encoding rules are summarized in Table 2.

| Information Sequence $(u_k)$ | Generic encoder state $(\sigma_k)$ | Sequence of the state of the encoder $(g_2)$ | Encoded signal $x_e(t)$ |
|---|---|---|---|
| 0 | $\Sigma_1$ | $\Sigma_1$ | $s_1(t)$ |
| 0 | $\Sigma_2$ | $\Sigma_2$ | $-s_1(t) = s_3(t)$ |
| 1 | $\Sigma_1$ | $\Sigma_2$ | $s_2(t)$ |
| 1 | $\Sigma_2$ | $\Sigma_1$ | $s_2(t)$ |

*Table 2*: summary of the encoding criteria for optical duo binary coding

Figure 7 shows the duo binary coded signal obtained from MOCSS software package and its power spectrum calculated from the discrete Fourier transform of the modulating voltage.
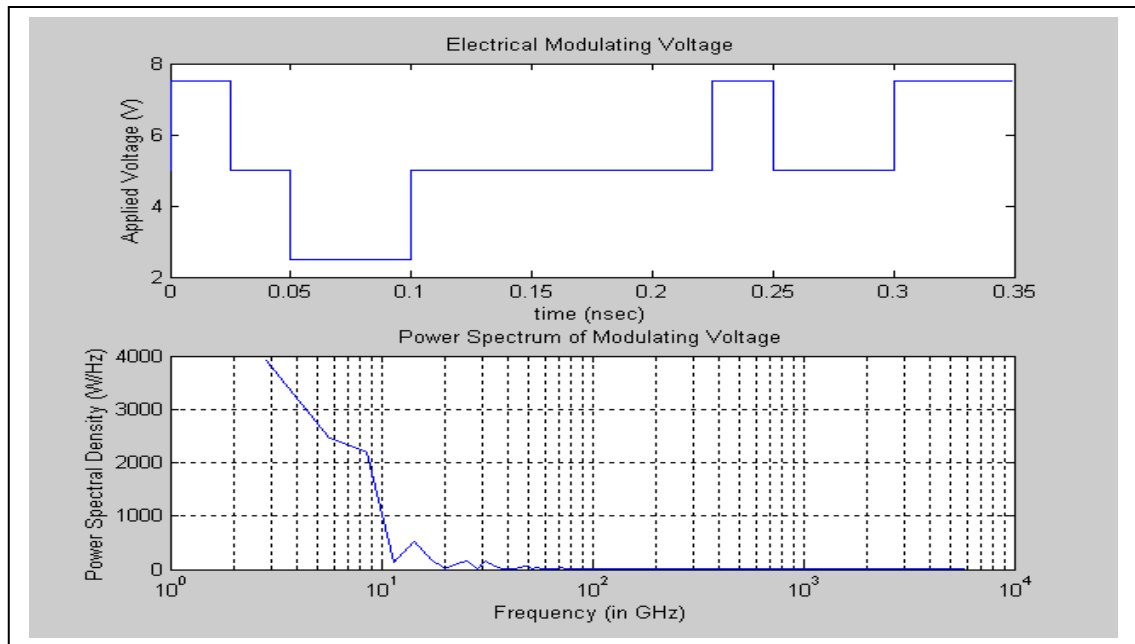
*Figure 7: Duo binary coded signal of '0 1 0 0 1 1 1 1 1 0 1 1 0' and its power spectrum*

The novel optical coded signal for arbitrary input data stream can be generated with four elementary signals while the elementary signals required to generate the duo binary coded signal is three. Order one of the novel optical code simulated in this paper use the middle level coefficient $\alpha = 0.5$. It is clear that the duo binary code is a special case of novel optical code with $\alpha = 0$.

3. EXTERNAL MODULATORS AS DWDM OPTICAL TRANSMITTERS

The role of the optical transmitter is to convert an electrical input "data" signal into the corresponding optical signal and then launched it into the optical fiber serving as a communication channel. The major components of optical transmitters are light sources, modulator and multiplexer. In Tb/s capacity DWDM optical networks external optical modulators must be used to minimize the spectrum of the laser source and provide ultra -

broad bandwidth (due to the fast electro optic effects). Furthermore these optical transmitters are multiplexed to form parallel streams of light waves propagating along the fiber.

In this section theoretical aspects of the advanced optical sources used in modern Tb/s capacity optical systems are explained with a description of modulation techniques and DWDM multiplexing. External modulation of novel optical coding and CS – duo binary (CS-DB) coding, using a Mach–Zehnder modulator is discussed in detail during the course of this section. Several factors should be considered when determining the choice of light sources for fiber optic systems (i) The wavelength of a signal source must fall within a transmission window of the optical fiber being used; (ii) The power must be high enough to span the distance to the first optical amplifier, regenerator or the receiver, but not so high to course non-linear effects in the fiber (iii) The range of wavelengths emitted by the source should not be so broad so that the dispersion limit the transmission.

Laser sources simulated in our platform are constricted mesa, distributed feed back laser (DFB) and bright soliton generator. For high performance, low dispersion and closer spacing of optical channels, lesser emission must be limited to a single longitudinal mode or equivalently to a single frequency. Despite the technological complexities, DFB lasers are routinely produced commercially, since they satisfy the above requirements. They are used in nearly all 1.55µm optical communication systems operating at bit rates of 2.5Gb/s or more.

The operating characteristics of the semiconductor lasers are well described by a set of rate equations that govern the interaction of photons and electrons inside the active region. Derivation of these rate equations generally starts from Maxwell's equations, together with a quantum – mechanical approach for the induced polarization. However the rate equations can

also be obtained by considering the physical phenomena through which the number of photons, P and the number of electrons N change with time inside the active region.

At low driving currents, simulated emission does not exceeded absorption and spontaneous emission dominates the output. The spectral range of this emission is broad. The minimum amount of gain necessary for the operation of the laser can be realized only when the laser is pumped above a threshold level. The current needed to reach this threshold is called the threshold current, $I_{th}$. There is a sharply defined increase in the output power at $I_{th}$. The threshold current is defined as,

$$I_{th} = (qV_a/\tau_c) [N_0 + 1/\Gamma a_0 v_g \tau_p] \qquad (12)$$

where, $q$ – electron charge ($1.6 * 10^{-19}$); $V_a$ – active layer volume ($1.5 * 10^{-16}$); $\tau_c$ – carrier lifetime ($3.0 * 10^{-10}$); $\tau_p$ – photon lifetime ($3.0 * 10^{-12}$); $N_0$ – carrier density at transparency ($10^{12}$); $\Gamma$ - optical waveguide confinement factor (0.4); $a_0$ – gain coefficient ($3.2 * 10^{-20}$); $v_g$ – guided lightwaves group velocity ($7.5 * 10^7$).

DFB lasers have a number of unique properties arising from the grating structure. In addition to their narrow line widths (typically 0.1 – 0.2nm), which make them attractive for long high bandwidth transmission paths, they are less temperature dependant than most conventional laser diodes. The grating tends to stabilize the output wavelength, which varies with temperature owing to changes in refractive index. Typical temperature caused wavelength shifts are just under 0.1nm/°C, which provides 3-5 times better performance than conventional laser diodes. DFB lasers are also more linear in their response than conventional laser diodes. Linearity minimizes intermodulation when several channels are

multiplexed for simultaneous transmission. For this reason DFB lasers have been used successfully in MOCSS to simulate 40Gbps per channel optical communication systems.

## 3.1    Modulation Techniques

Transmitter performance depends strongly on how the light source is modulated. Most optical transmitters are modulated by signals that change the amplitude or intensity of the light they generate. Two main modulation techniques used in optical fiber transmitters are,(i) Direct modulation and (ii) External modulation. In direct modulation, diode laser sources present additional complications because of the nature of laser emission. As shown in Figure 3, laser emission begins after the drive current exceeds a threshold value. If the laser is turned completely off by shutting down the drive current, it won't start emitting again until the drive current exceeds the threshold. These processes problems at high speeds, where laser transmitters are desirable, because the laser would not start emitting light until sometime after the drive current started to rise.  To avoid this problem, lasers normally have two sources of drive current, which add together. One produces a steady bias current, which typically slightly exceeds laser threshold. The other is variable signal current, which actually modulates the laser output by increasing the current above the bias level.

Direct modulation is ideal for inexpensive transmitters, but it causes an undesirable wavelength chirp, which causes excessive chromatic dispersion at high speeds. In addition lasers, develop undesirable relaxation oscillations at frequencies of a few gigahertz, which limits the maximum frequency for direct modulation. In addition to the data rate average output power, extinction ratio between "on" and "off" power is all limited in direct modulation.

These limitations are most serious in high performance systems. Output power and the extinction ratio limit receiver performance and spacing between optical amplifiers. Modulation speed limits the transmission capacity and non-linearity can distort analog signals. To avoid these practical limitations external modulators are needed at higher speeds, or when the light source cannot be directly modulated.

In external modulation a steady laser beam is modulated with an external modulator, which changes the intensity of the light in response to an external control signal. Modern fiber optic systems use two main families of modulators: electro absorption modulators and electro optic modulators

Electro optic modulators rely on changes in the way certain planner wave guides carry light, while electro absorption modulators are semiconductor diodes that in their internal structure resemble lasers, but are switched between states that transmit and absorb light. The electro absorption modulator is a wave-guide device with a structure similar to that of an edge emitting semiconductor laser. The laser and the EA share the active layer, and light generated within the laser stripe is coupled directly to the modulator wave-guide. When the laser is forward biased, current flows through it, causing current carriers to recombine and generate light. The modulator is operated with a reverse bias. When the modulator is unbiased, no current flows and it is transparent to light at the laser wavelength. However when the bias voltage is applied, the laser light can produce electron hole pairs that are pulled in opposite directions by the bias voltage, causing a net absorption at the laser wavelength. Increasing the bias increases the absorption, blocking the beam.

The laser and the modulator are electrically isolated from each other. A steady current drives the laser, so it generates a steady optical output. The input signal drives the modulator. For

zero applied voltage, the optical output is at his highest voltage. Applying a higher voltage to the modulator increases light absorption. (i.e. high voltages generates no light output)

For electro optic modulators, Refractive index of certain materials changes with the variation of the electric field applied to them. This effect is used as the electro optic effect and it is used in electro optic modulators. The velocity of light on a material is the speed of light in a vacuum divided by the refractive index, so increasing the refractive index, slows down the light; and reducing the refractive index speeds up the light. The change is proportional to the voltage applied to the material. Commonly used material in electro optic modulators is lithium niobate ($LiNbO_3$) and the modulator is commonly called as the Mach – Zehnder Modulator. Wave-guides are made by diffusing titanium or hydrogen into the lithium niobate, raising the refractive index of a narrow stripe that forms a wave-guide. In Tb/s capacity optical communication systems the chromatic dispersion in standard single mode fibers (SMF) together with the polarization mode dispersion (PMD) are the main limiting factors to higher transmission bit rate and distance, limiting the system performance. One technique to compensate the chromatic dispersion in the SMF is pre-chirping using negative chirp devices, such as electro optical Mach Zehnder modulators. [7]. Lithium niobate external modulators provide the required bandwidth for high bit rate and the way to minimize the effect of fiber dispersion due to the adjustable – chirp operation [8]. Due to the electro optic effect in a wave-guide, a phase shift in a light wave can be created by applying an electric field across the wave-guide. This phase shift is normally measured by

$\Delta\phi = 180° * \dfrac{V}{V_\pi}$ where $\Delta\phi$ is the phase shift and $V$ is the applied voltage and $V_\pi$ the voltage

required for a phase shift of a half wavelength or 180°. Due to this electro optic effect, the

light modulates its phase but not its intensity. To modulate the intensity, Mach Zehender (MZ) modulator split its input light equally between a pair of parallel wave-guides.

The modeled MZ modulator is a fabricated fiber with a ridge height of H=3.3µm, and electrode thickness of T = 10µm, because it gives an optimal performance with a bandwidth of 30GHz, a small conductor loss and fast interaction with the guided electromagnetic wave. The 180° or $\pi$ phase shift voltage, $V_m(t) = V_\pi$, is 5V and insertion loss due to coupling losses at the input and output connector is 6dB. $V_\pi$ is the driving voltage, which achieves a $\pi$ phase difference between the two light waves and results (theoretically) a complete cancellation of the carrier wave at the output port. Therefore $V_{m,ON} = 0$ and $V_{m,OFF} = V_\pi$ and the power transfer or extinction ratio characteristics is modeled by the following relation ship as a function of the driving voltage.
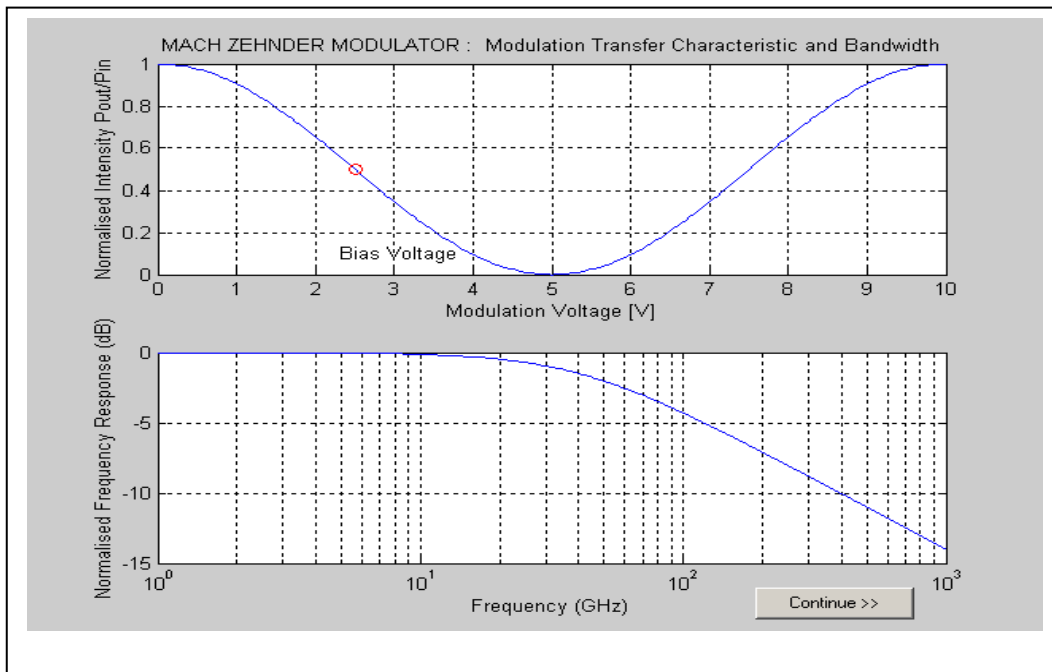
*Figure 8*: Transfer characteristics of MZ modulator, $P_{out} = P_{in} (\cos^2 \dfrac{\pi V_m(t)}{2V_\pi}$.

3.1.1.1   External modulation of novel optical line coded signal

Novel optical line coded signal is modulated by the MZ modulator biases at its half power point, $3V_\pi/2$ as shown in Figure 9. The optical power spectrum of the modulated carrier is calculated as

$$E(t) = \sqrt{P_{out}(t)} \exp(j(\varpi_c t + \phi)) \tag{13}$$

Where $P_{out}(t)$ is the signal power, $\omega_c$ is the optical carrier frequency $\phi$ is the phase shift produced by the modulator [9]. $E(t)$ describes the optical field at the modulator output port and at the transmission fiber input.
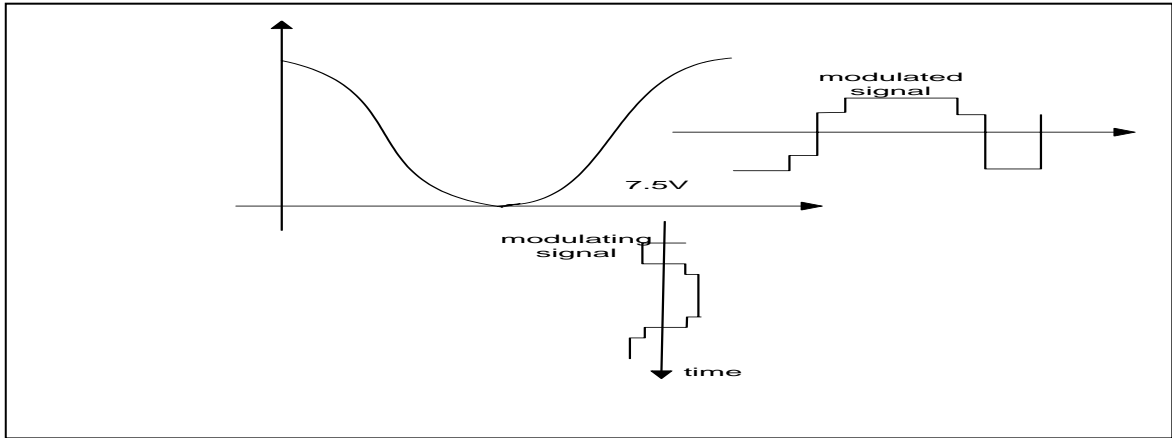


*Figure 9*: Transfer characteristics and biasing arrangement of novel optical line coding

Modulated signal output of the MZ modulator and the power spectrum of the modulated signal are given in Figure 10.
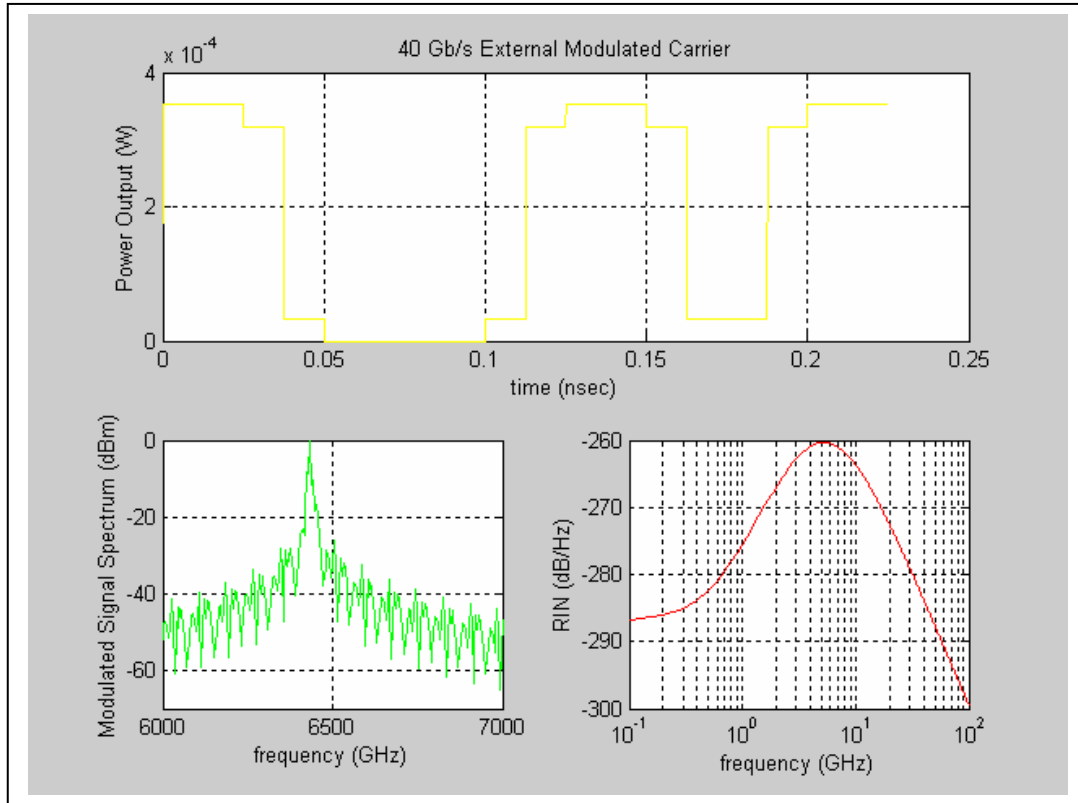
*Figure 10: Modulated signal (01001011) output and the power spectrum.*

### 3.1.1.2   Carrier suppressed duo-binary modulation

As illustrated in the previous section, duo-binary coding uses a three level signal to reduce the required electrical and optical bandwidth. Reduced bandwidth increases the transmission distance because the effect of group velocity dispersion scales as $f^2L$ where f is the modulation frequency and L is the fiber length. The duo binary coded signal is modulated with a push pull type $LiNbO_3$ MZ modulator with a bandwidth of 30dB. Simple and efficient method is used to produce the double side band suppressed carrier duo binary modulated signal using a single off the shelf optical component [9]. The phase shift is applied to the MZ modulator in an anti symmetric fashion so that the induced side bands from the two branches add when the carrier component cancel. Suppressed carrier is achieved by biasing the MZ

modulator at $V_0 = V_\pi$ , as shown in the Figure 11, such that the carrier components cancel at the output coupler of the modulator.
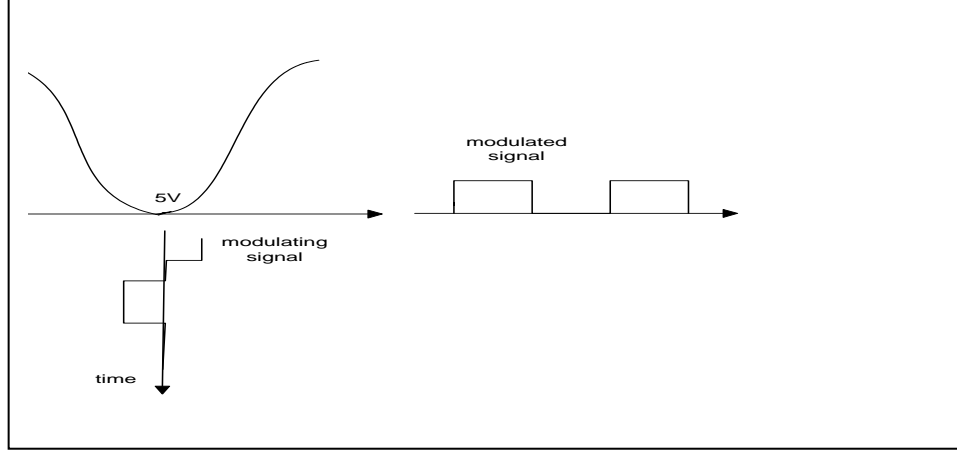


*Figure 11*: Biasing the MZ modulator to generate duo binary optical signal

Let assume the difference in phase between the two braches of the modulator is sinusoid added to the dc bias $V_0$ i.e. $\phi(t) = m\ cos(2\pi v_c t) + \phi_0$ where $v_c$ is the frequency of the

modulation tone, modulation index m is defined as $m = \dfrac{\pi V_m}{V_\pi}$ and $\phi_0 = \dfrac{\pi V_0}{V_\pi}$ where $V_m$ is the modulator driving voltage and $V_\pi$ is its half wave switching voltage. If the modulator is biased so that the electric field strength is linearly related to the input voltage (i.e. $V_0 = V_\pi$ and hence $\phi_0 = \pi$) there will be no carrier component in the modulated signal. Finally the modulated signal will be,

$$E_{sig}(t) = \sqrt{P_{out}}\ \sin[m\cos(2\pi V_m t)]\cos(2\pi v_c t) \tag{14}$$

Hence the output of the MZ modulator will be a double side band suppressed carrier (DSB-SC) signal. [9]. Modulated duo binary waveform ant its power spectrum is shown in the Figure 12, and the carrier suppression is clearly indicated in the power spectrum.
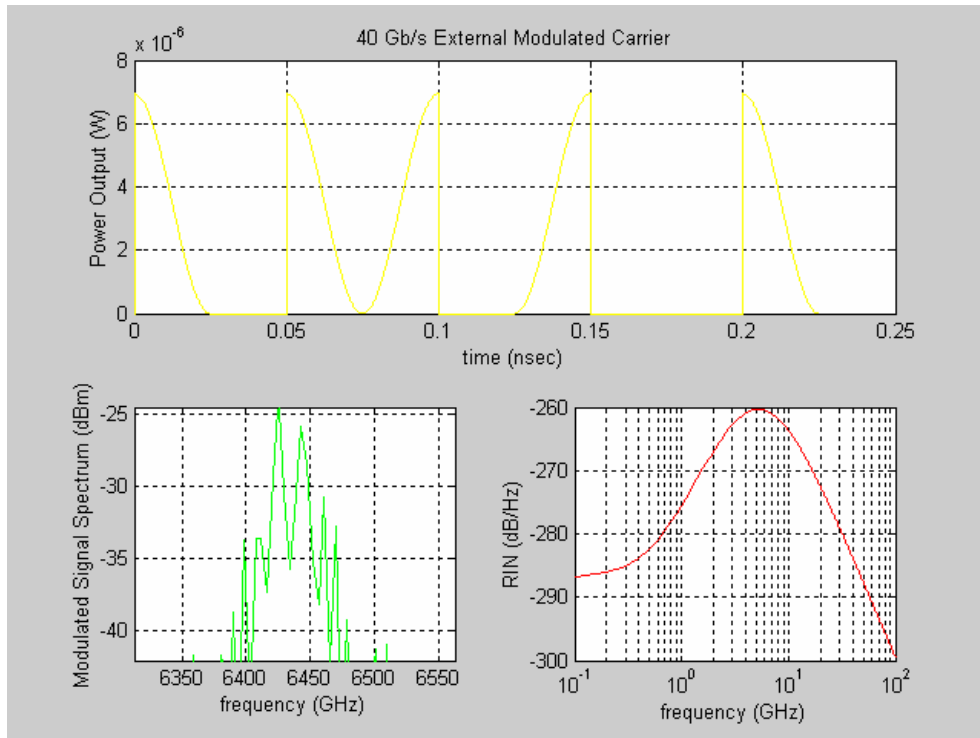


*Figure 12*: Modulated duo binary signal (01001011) and its power spectrum> the centre of the spectrum is shifted to 1550 nm.

Wavelength division multiplexing (WDM) operates by sending multiple light waves (frequencies) across a single optical fiber. Information is carried by each wavelength, which is called a channel, through either intensity (or amplitude) or phase modulation. At the receiving end, and optical demultiplexer is used to separate the frequencies, and the information carried by each channel is extracted separately. Binary digital signal, which is a full on/off intensity modulation, can also be carried by each individual channel, although the bit rate is expected to be lower than the intensity or phase modulation. As in conventional

frequency division multiplexing (FDM) carriers can be mixed onto a single medium because light at a given frequency doesn't interfere with light at another frequency with in the linier of approximation.

The modulator encodes digital data into waveform symbols through either intensity or a phase modulation method, and the modulator reveres the process to obtain digital data. The switch nodes consist of add/drop multiplexes and demultiplexes, wavelength switches and wavelength converters. The multiplexers are used to combine the signal of different wavelengths for transmission. The demultiplexes are used to separate and filter different wavelength channels. The wavelength switch cross connects the input channels to the desired output channels. The function of the wavelength converters is to convert the over – demand wavelengths to free wavelengths in a given fiber to achieve high channel utilization.

The channel density is a key variable in WDM systems. The optics provides uniformly spaced slots for optical channels, although the system may not use all those slots. The spacing of the slots determines the density. The international telecommunication union grid has specified one set of standard center frequencies separated by 100GHz, which corresponds to about 0.8nm in the erbium fiber amplifier band. Some commercial systems have 50GHz grid spacing, ev ntually reaching 25GHz and even 12.5GHz.

Typically spacing of 200GHz or less is called dense wavelength division multiplexing (DWDM). This allows many more channels to be multiplexed in the spectrum.  Narrowing the spacing it is more difficult and more expensive to make multiplexing and de-multiplexing optics. On the other hand it will more utilize the expensive system bandwidth and more information (cannels) can be sent in the usable wavelength region.

In paper, 64 novel optical line coding modulated signals were multiplexed with 100GHz spacing (ranging from 1535.04nm – 1586nm) and 81 optical duo-binary coded signals were multiplexed with 50GHz spacing (ranging from 1535.04nm – 1567.54nm) before transmitting them through the optical channel. Multiplexed signals are shown in Figure 13 and Figure 14.
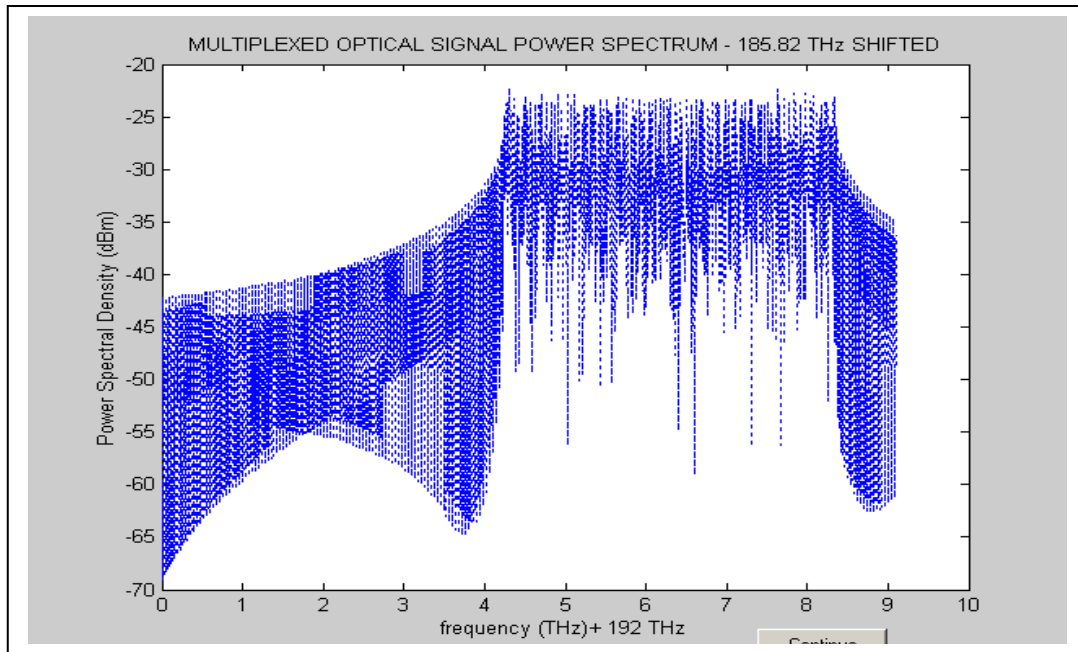


*Figure 13*: DWDM Multiplexed signals from MOCSS (64 channels of novel multi-level optical coding with 100 GHz spacing)
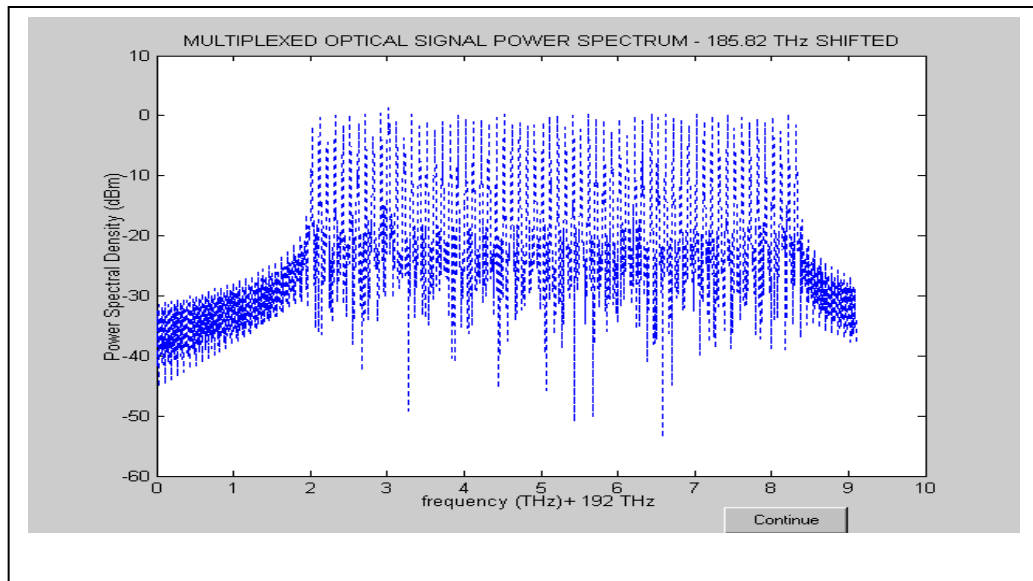
*Figure 14*: DWDM Multiplexed signals from MOCSS (81 channels of CS –

*Duo-binary with 50 GHz spacing)*

The Mach–Zehnder modulator, which is biased at 2.5 V, can be used to modulate novel optical coded signal and it should be biased at 5V for the carrier suppressed duo binary modulation. Due to the suppression of the unwanted carrier component in CS – duo-binary (CS-DB) modulation, power spectrum of the modulated signal is less than *–25 dBm*. DWDM multiplexed power spectrums of both modulation techniques have been shown to be spectrally very efficient and well suited to be high capacity transmission.

4. COMPARISION OF THE PERFORMANCE OF DIFFERENT LINE CODING TECHNIQUES

The intention of this section is to compare the performance of Novel optical line codes and optical duo-binary codes with conventional return to zero and non-return to zero line codes in dispersion compensated fiber optic links. In particularly carrier suppressed duo-binary and optical line coded signal transmission have been investigated in long haul 40 Gb/s per

channel WDM systems with paying strong attention to chromatic dispersion, nonlinear effects, attenuation, noise and spectral efficiency.

## 4.1 Dispersion tolerance comparison

High-speed long distance WDM trunk lines over standard single mode fiber are necessarily dispersion compensated using dispersion compensating fiber (DCF). Therefore dispersion tolerance of each coding format in highly dispersive environment should be investigated. Our simulated experimental setup is shown in Figure 15. The DFB laser diode is used with wavelength 1550nm and the generated lightwaves are then modulated by a single or dual arm Mach–Zehnder modulator operating in a push pull configuration. For RZ, NRZ modulation, electrical signals are applied to the modulator at 2.5 V (i.e. $V_{bias} = V_\pi/2$). In the case of carrier suppressed duo-binary, three level electrical signal is applied at maximum extinction, i.e. at $V_{bias} = V_\pi$, while in the case of novel optical line coding modulating signal is applied at $V_{bias}$ = 7.5V. The transmission line consists of single mode fiber with span loss $\alpha = 0.50463$ $dB/km$. The nonlinear coefficient $\gamma$ is $2Km^{-1}W^{-1}$. Chromatic dispersion of the transmission line D is 17ps/nm/km with dispersion slope of $dD/d\lambda = 0.08ps/nm^2/km$. Parameters of the single mode fiber used in this simulation is given in Table 1.
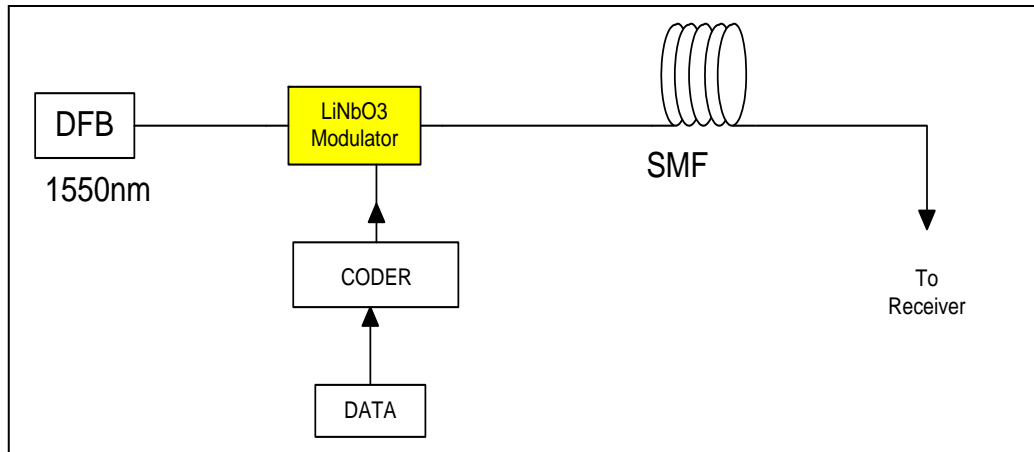
*Figure 15*: Simulation setup with one wavelength channel

| SMF parameter | Value |
|---|---|
| Zero material dispersion | 1270nm |
| Zero total dispersion | 1300nm |
| Dispersion at 1550nm | 17ps/nm/km |
| Core radius | 4.3μm |
| Core index | 1.4487 |
| Fiber loss | 0.50463dB/km |

*Table 3*: Single mode fiber parameters

Signal power spectrum and the modulated signal of each modulation scheme is given in Figure 16 and Figure 17.
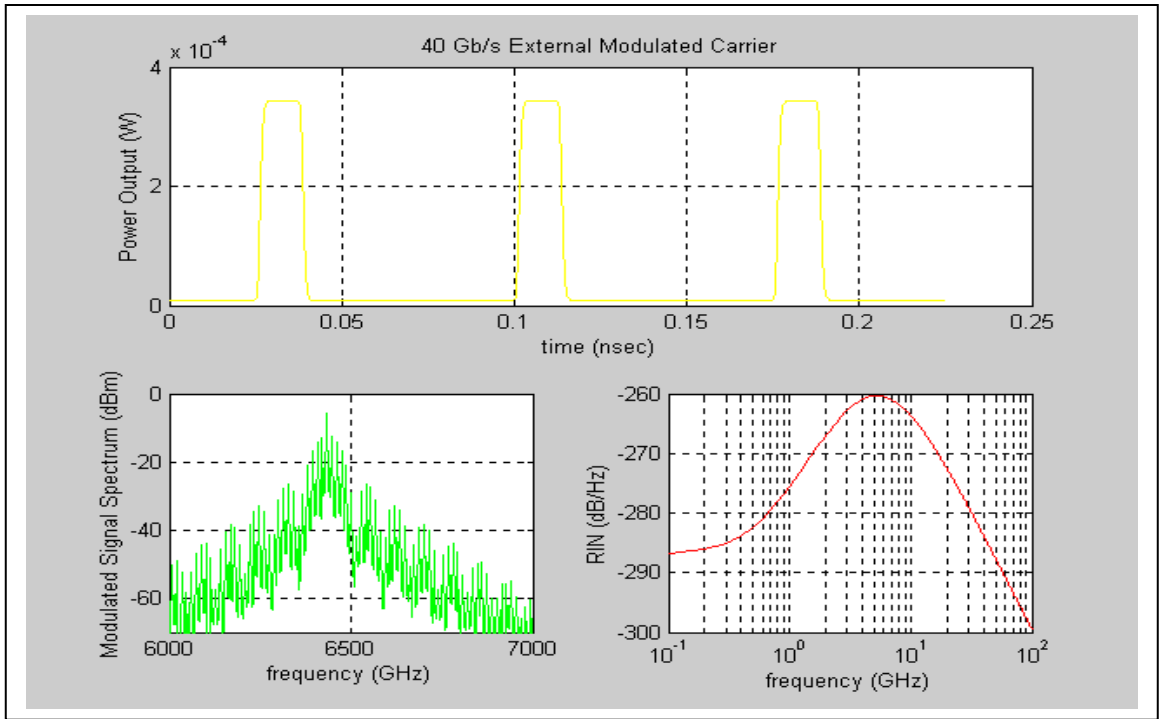
(a)
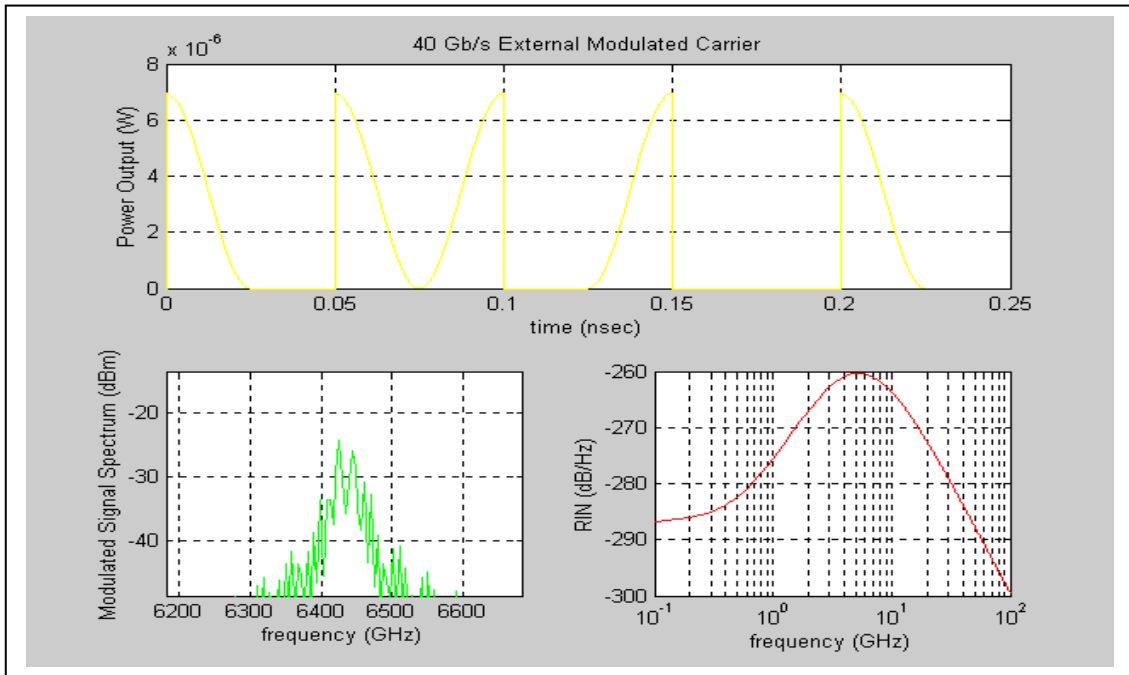


(b)
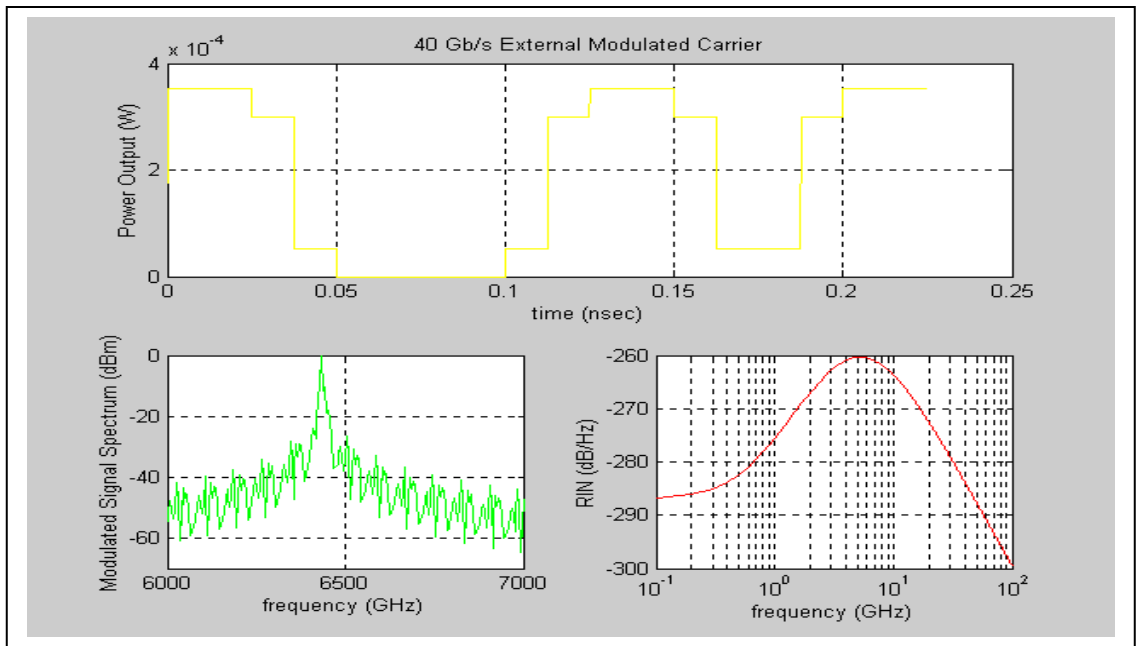
(c )

*Figure 16: Modulated signal and the power spectrum of (a) RZ (b) duo- binary and (c) multi-*

*level  signals*

From the power spectrum of the signals it is clear that the reduction in the power spectral density less than –20dBm of the duo binary-coded signals is due to the suppression of the carrier signal. This reduction enables the system designers to use optical amplifiers immediately after modulation.
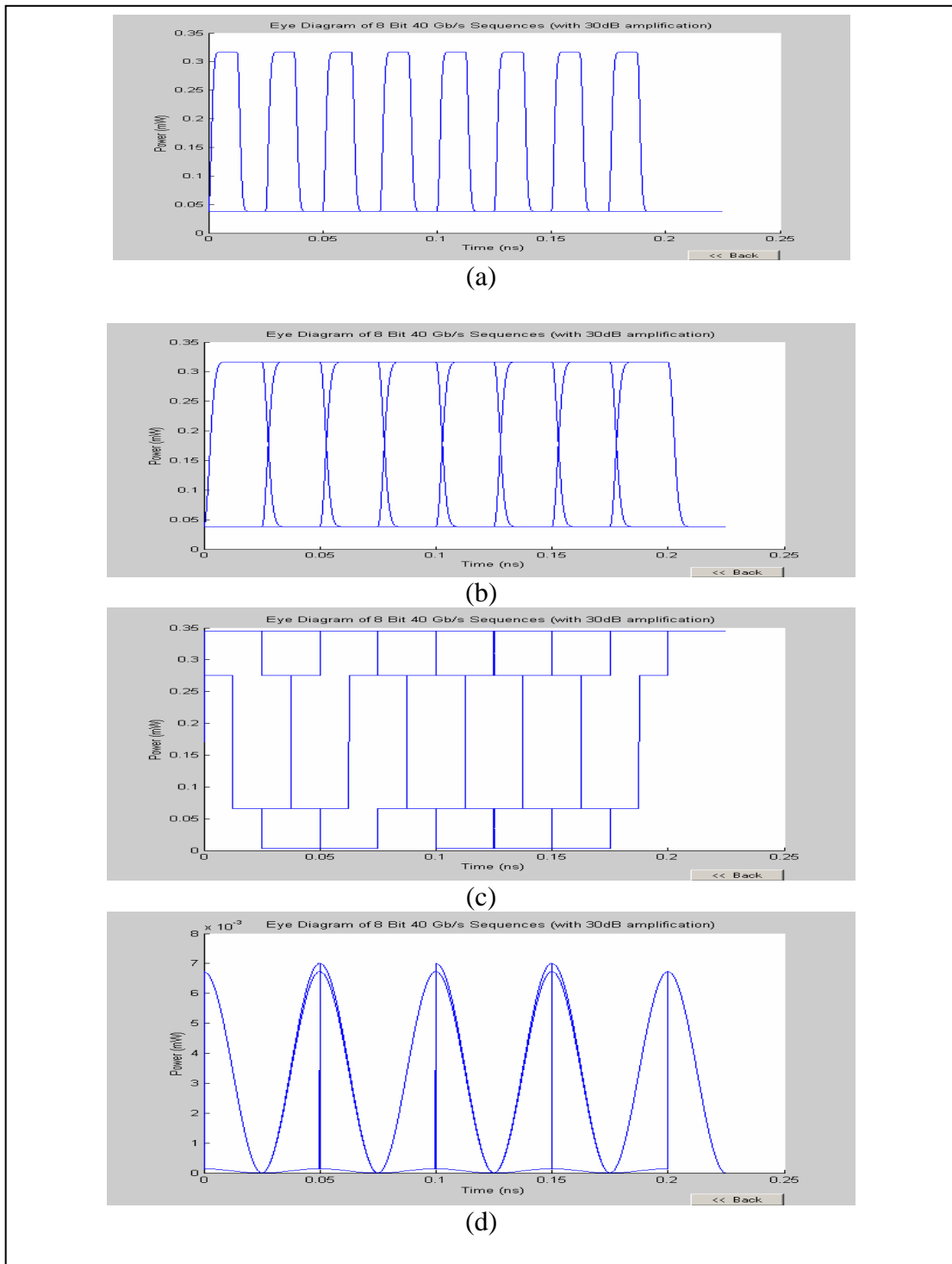
*Figure 17*: Back to back system eye diagrams for (a) RZ (b) NRZ (c) multi-level optical

coding (d) CS- duo binary modulation techniques

Modulated signals were transmitted in step of 5km distance and the bit error rate was calculated. The Q-factor is plotted in the Figure 22.
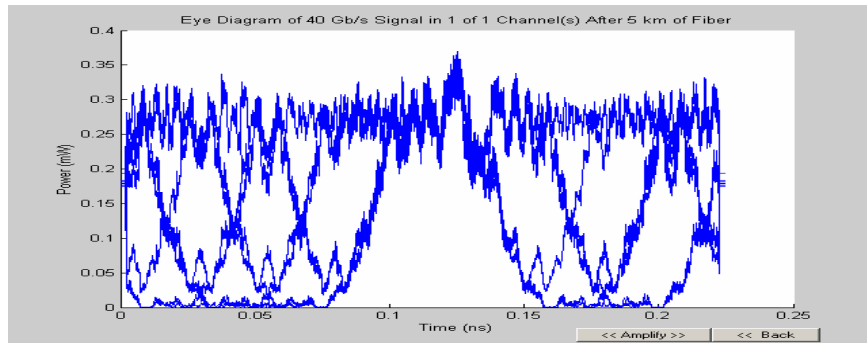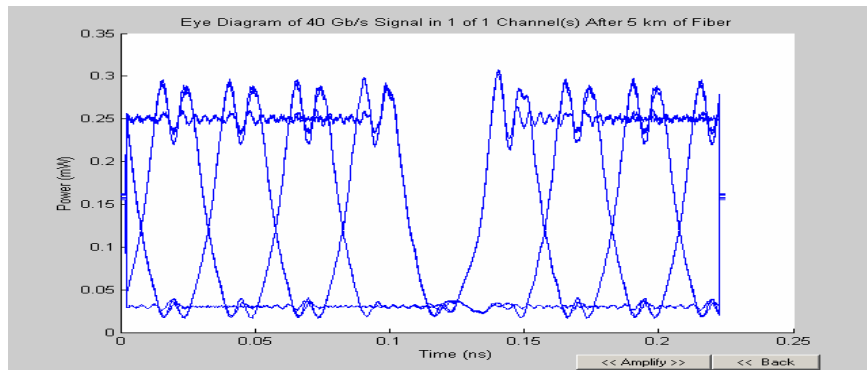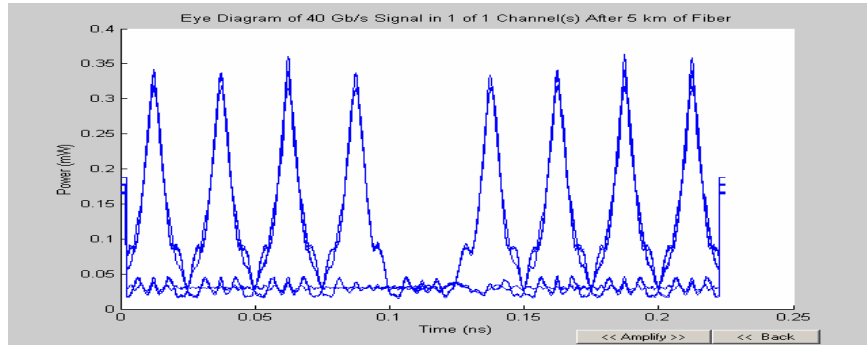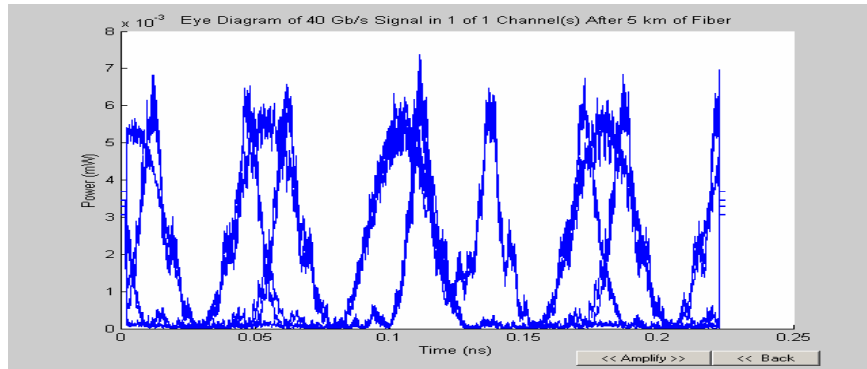
*Figure 18*: Eye diagrams of RZ, NRZ, Novel optical coding and CS – duo binary modulated

signals after 5 Km of transmission
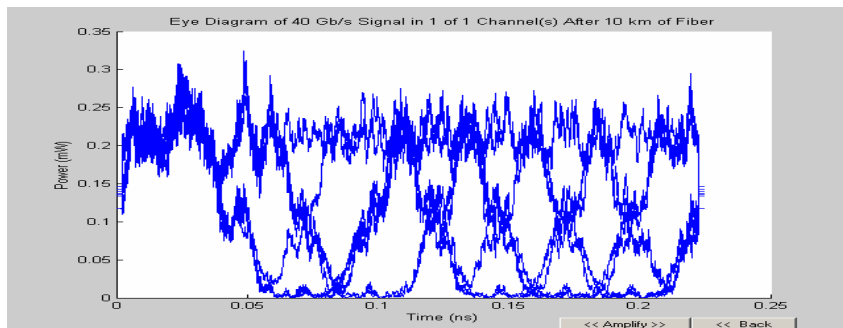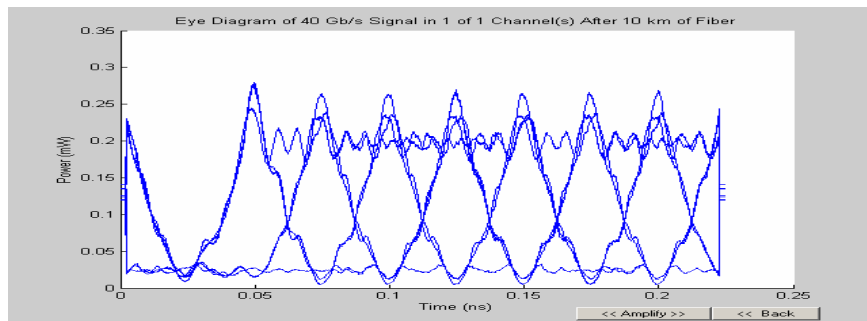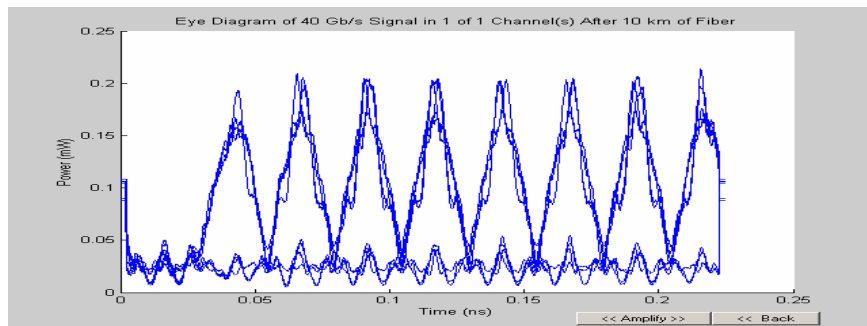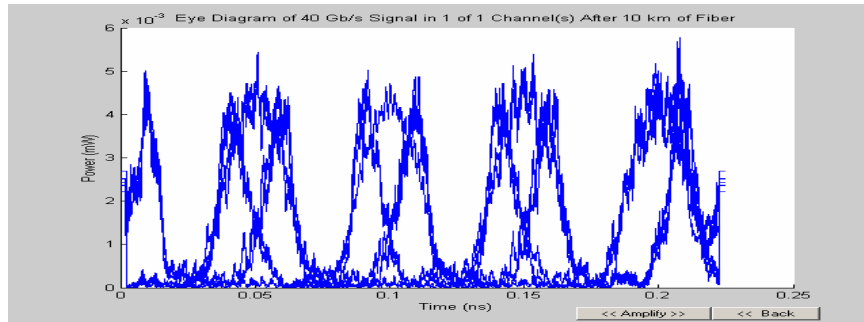
*Figure 19*: eye diagrams of RZ, NRZ, Novel optical coding and CS – duo binary modulated

signals after 10 Km of transmission
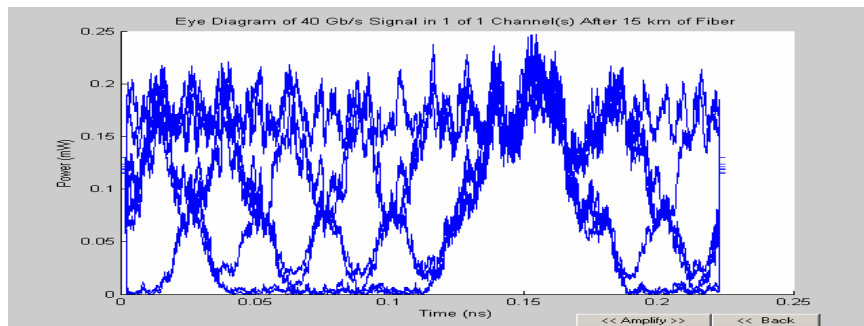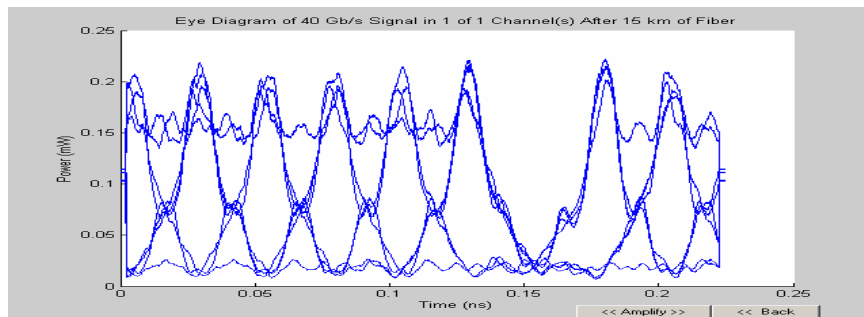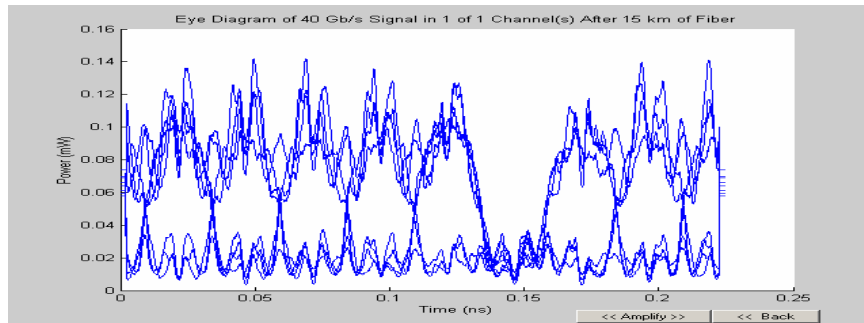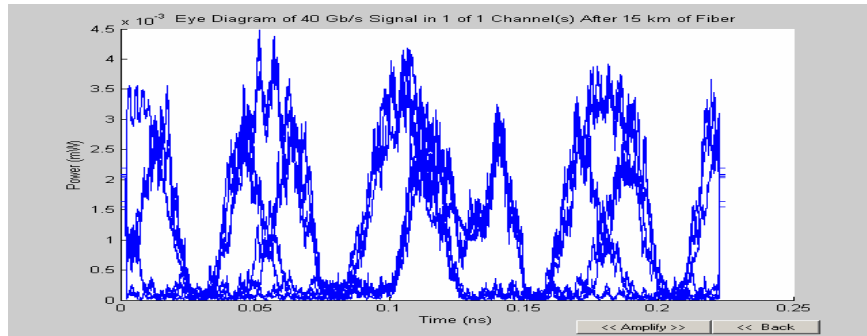
*Figure 20*: eye diagrams of RZ, NRZ, Novel optical coding and CS – duo binary modulated

signals after 15 Km of transmission
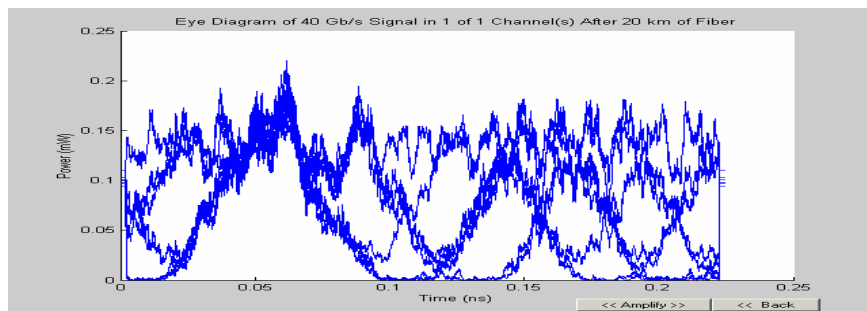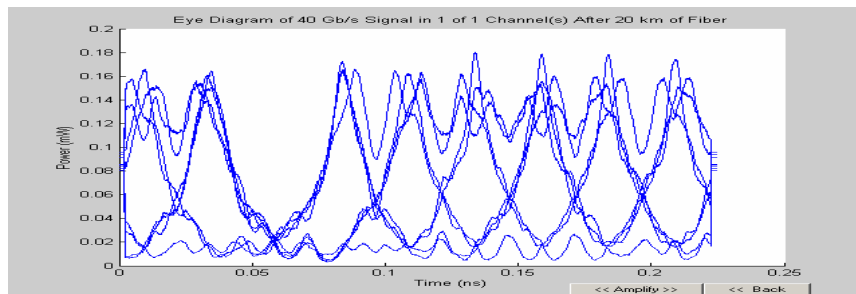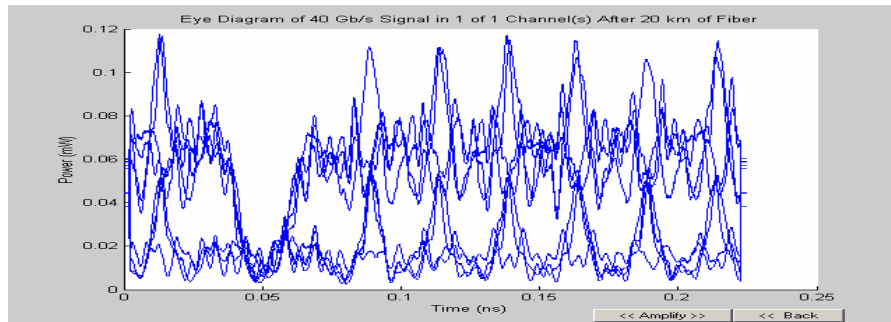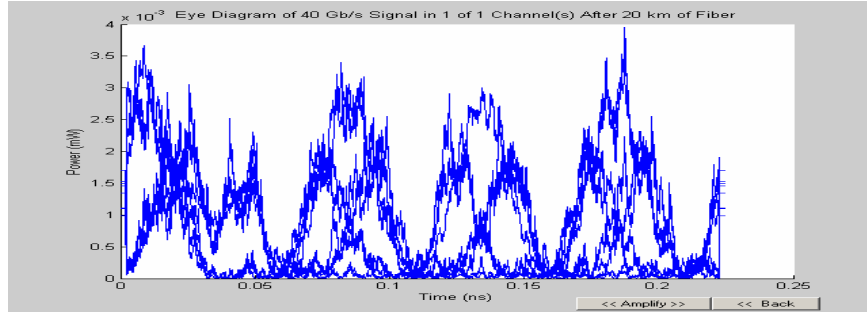
*Figure 21*:Eye diagrams of RZ, NRZ, Novel optical coding and CS – duo binary modulated

signals after 20 Km of transmission

**The Graph of Q factor Vs distance**
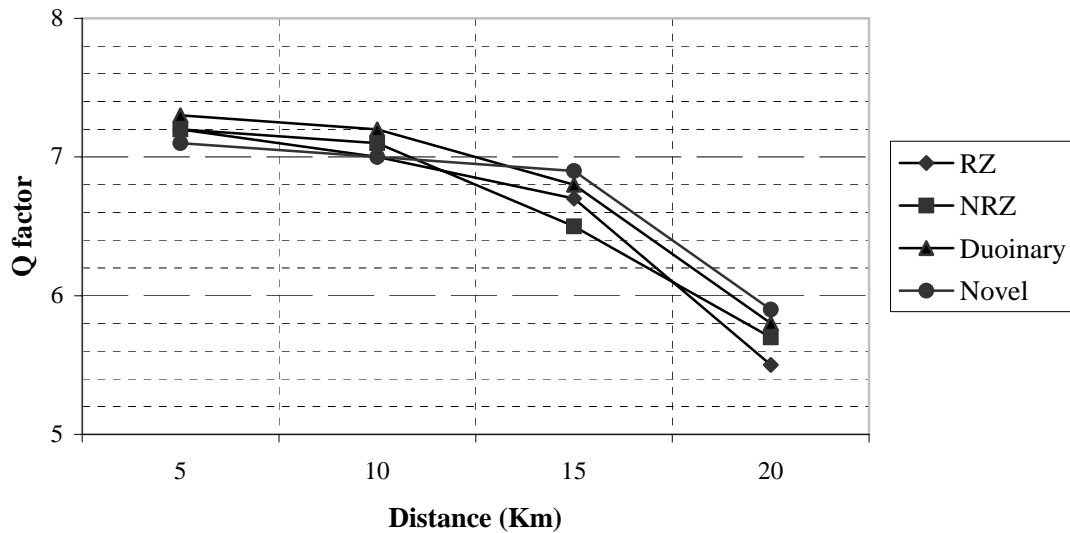


*Figure 22*: Q-factor vs distance (without dispersion compensation) for RZ, NRZ, Novel

optical coding and CS – duo binary modulation

4.2     Non linear tolerance measurement

Light waves transmitted through a fiber have little interaction with each other, and are not

changed by their passage through the fiber (except for absorption and scattering). However

there are exceptions arising from the interactions between light waves and the material

transmitting them, which can affect optical signals. These processes generally are called non-linear effects because their strength typically depends on the square of intensity. Therefore these effects will be significant when the power increased or when it is concentrated in a small area, such as the core of an optical fiber. Brillouin scattering, self phase modulation and the cross phase modulation are the more significant non linear effects that should be consider in optical transmission systems. Brillouin scattering occurs when signal power reaches a level significant to generate tiny acoustic vibrations in the glass. This can occur at powers as low as a few mW in single mode fiber. It can occur when only a single channel is transmitted.

Variation of the refractive index with the light passing through it causes intensity modulation of an optical channel to modulate the phase of the optical channel that creates it, and the effect is called self phase modulation. This effect also can occur in single channel systems.

Systems carrying multiple channels are vulnerable to cross phase modulation. Variation in the intensity of one optical channel cause changes in the refractive index affecting other optical channels. These changes modulate the phase of light on other optical channels.

When the channel spacing is less than 80GHz system limitations are caused only by single channel limitations and there are no further impairments due to multi-channel effects. At the channel spacing less than 80GHz multi-channel effects occur.
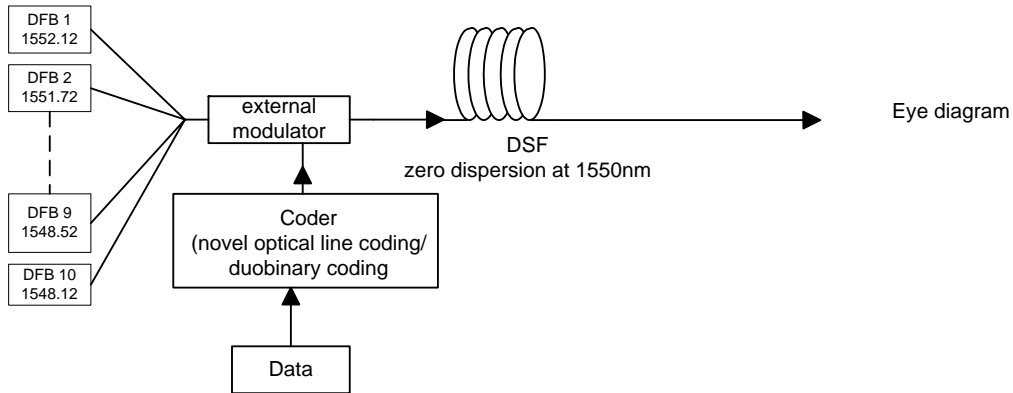
*Figure 23*: Simulation setup with ten channels and DSF

To evaluate the nonlinear tolerance of different line coding techniques, modulated signals were transmitted through dispersion-shifted fiber (DSF) with zero dispersion at 1550nm for 50km. Since the dispersion is zero, resultant distortion is mainly due to the nonlinear effects. Parameters of the DSF is given in the Table 2

| Parameter | Description |
|---|---|
| Fiber core material | Type E (Quenched $SiO_2$) |
| Dispersion at 1550nm | Zero |
| Core index | 1.444 |
| Delta value | 0.64416% |
| Diameter | 4.4612μm |

*Table 4 Parameters of dispersion shifted fiber (DSF)*

To investigate the effect of Brillouin scattering and self phase modulation single channel was transmitted along the DSF and amplified to different power levels. And the resultant eye diagrams after 50km are given in Figure 24 to Figure 26

To investigate the effect of cross phase modulation ten channels were multiplexed using WDM technology with 50GHz spacing, and transmitted along the DSF and injected 100dBm power. The resultant eye diagrams after 50km is given in Figure 27 to Figure 28.
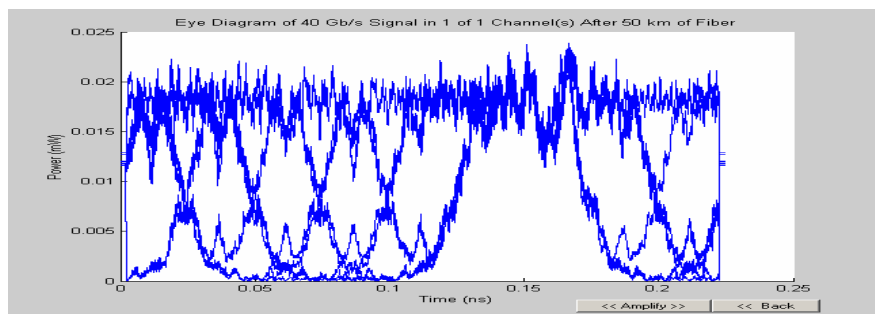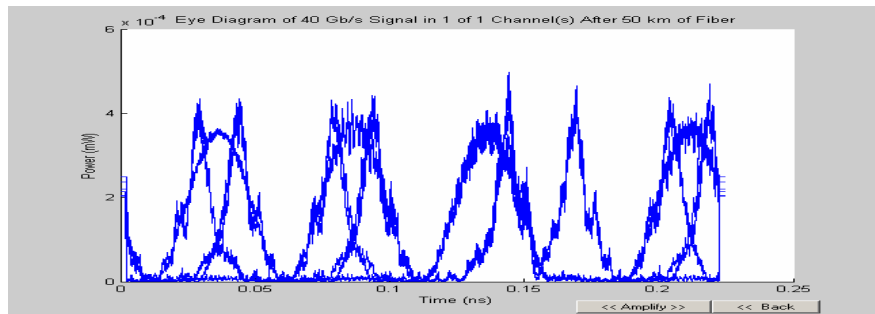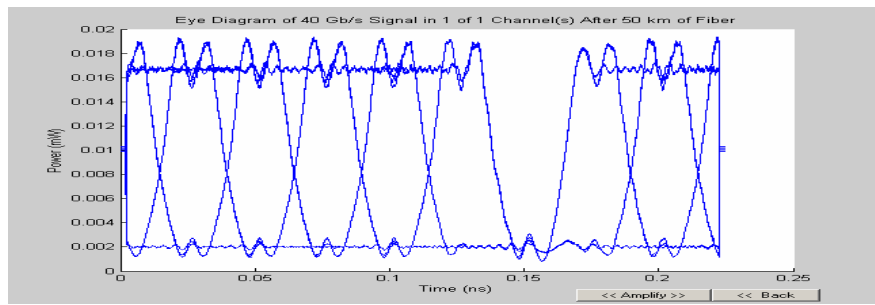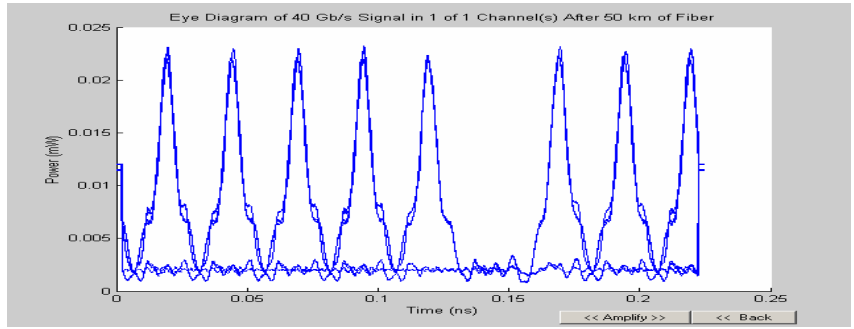
*Figure 24: Eye diagrams at 50 Km for RZ, NRZ, CS – duo binary and Novel optical coding*
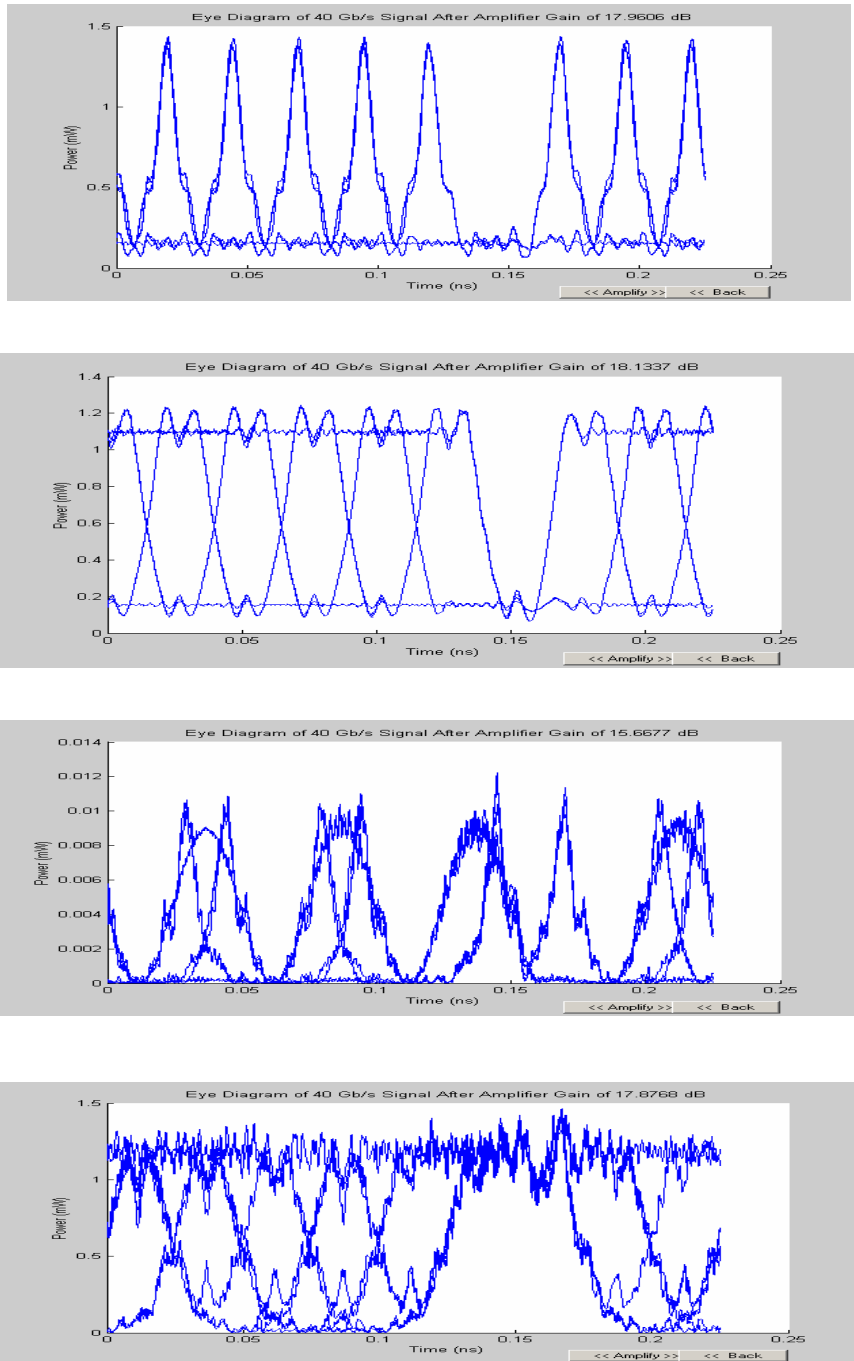
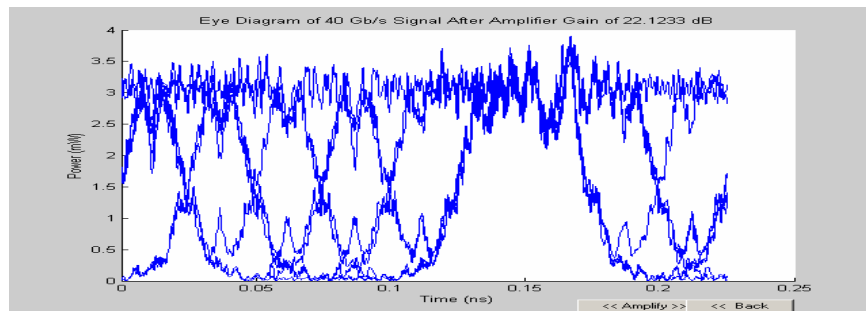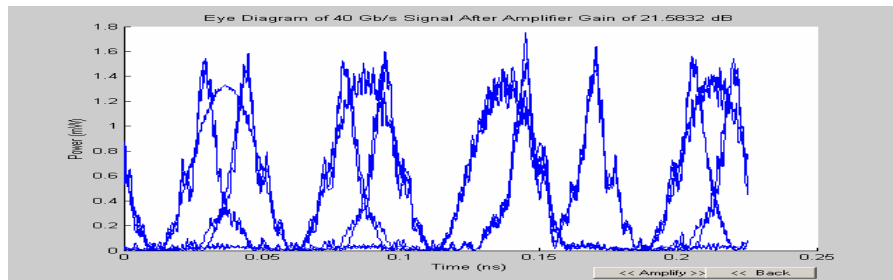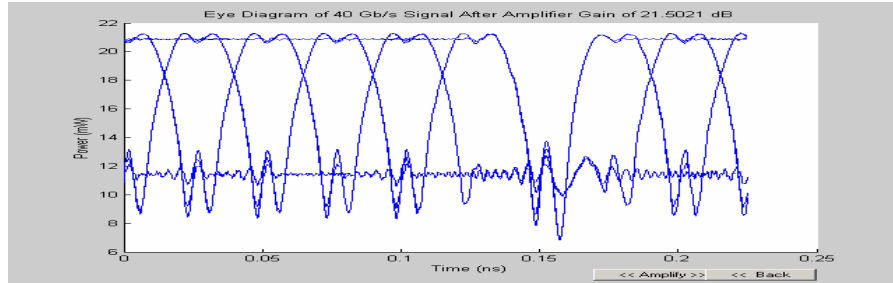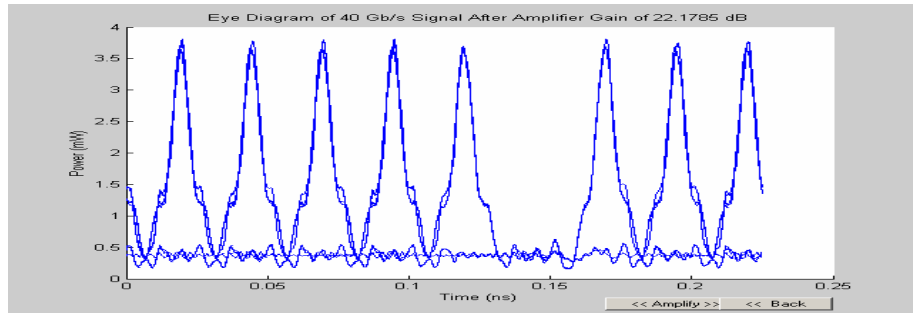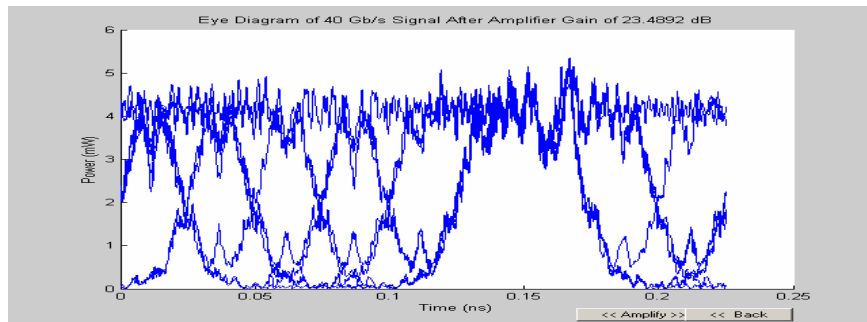*Figure 25: Eye diagrams at 50 Km after injecting 10dBm power for RZ, NRZ, CS – duo binary and multi-level coding*

*Figure 26: Eye diagrams at 50Km after injecting 15dBm power for RZ, NRZ, CS – duo binary and multi-level optical coding*
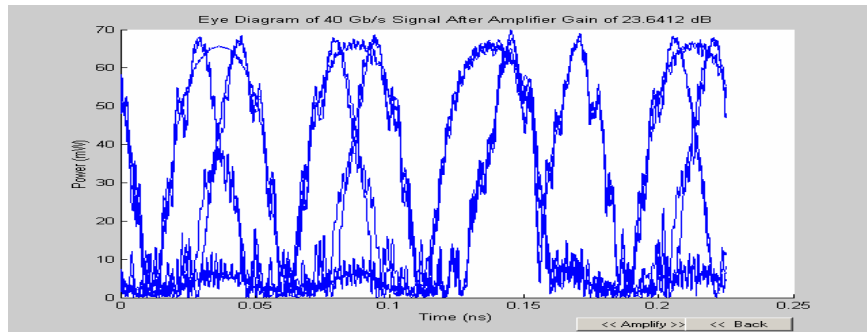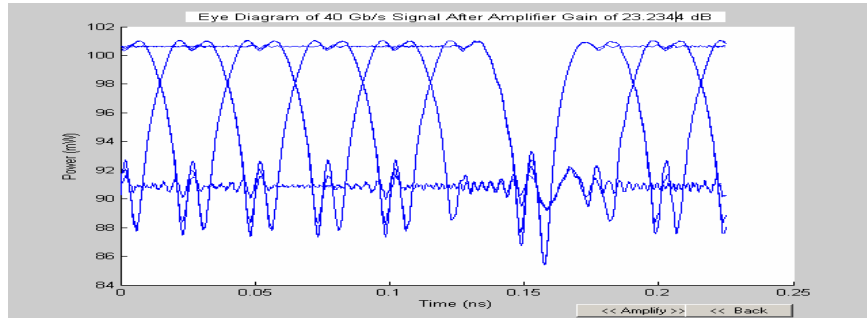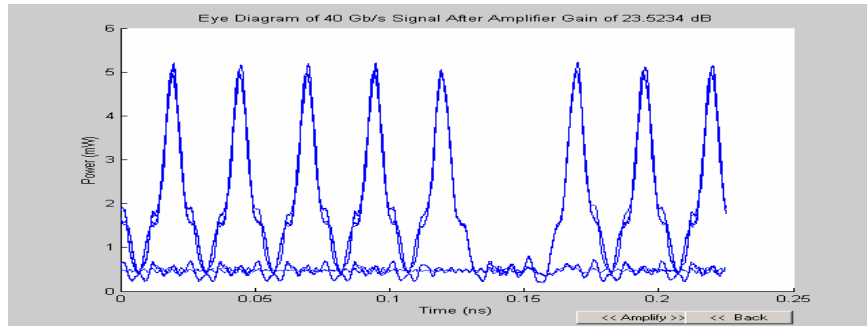
*Figure 27: Eye diagrams at 50 Km after injecting 20dBm power for RZ, NRZ, CS – duo binary and multilevel optical coding*
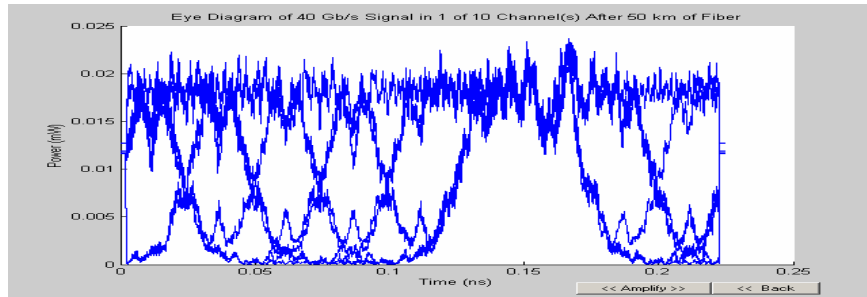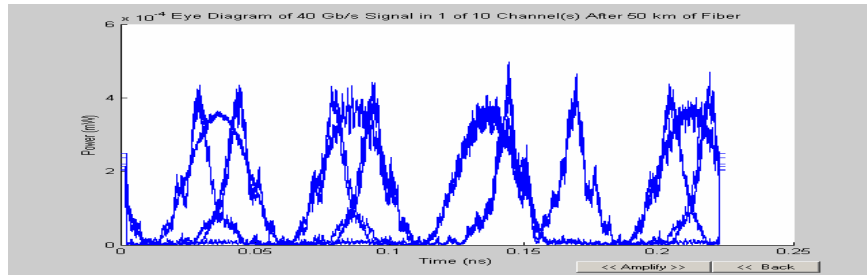
*Figure 28: Eye diagrams at 50 Km for 10 channels of CS – duo binary and multi-level*
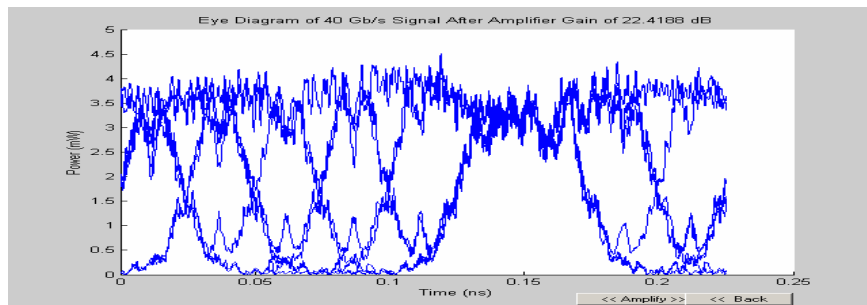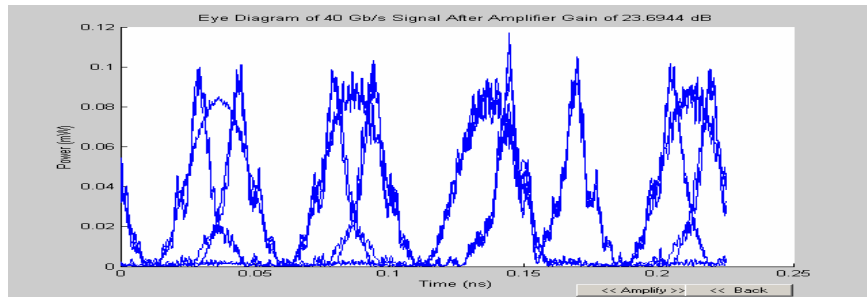
*optical coding.*





*Figure 29 Eye diagrams at 50Km after injecting 20 dBm for 10 channels of CS – duo binary*

*and multi-level optical coding*

100GHz spaced 40Gbit/s x 65 WDM transmission over 100km dispersion managed fiber using Novel optical line code (order one)

The block diagram in *Figure 30* shown below demonstrates 2.60Tbit/s WDM transmission using 65 channel multiplexed 40Gbit/s novel optical line coded signals over a 70 Km single mode fiber (SMF) and 30 Km of dispersion compensation fiber (DCF). Transmitted 46 channels are from 1535.04nm (195.30THz) to 1586.20nm(189.00THz) with 100GHz channel spacing.
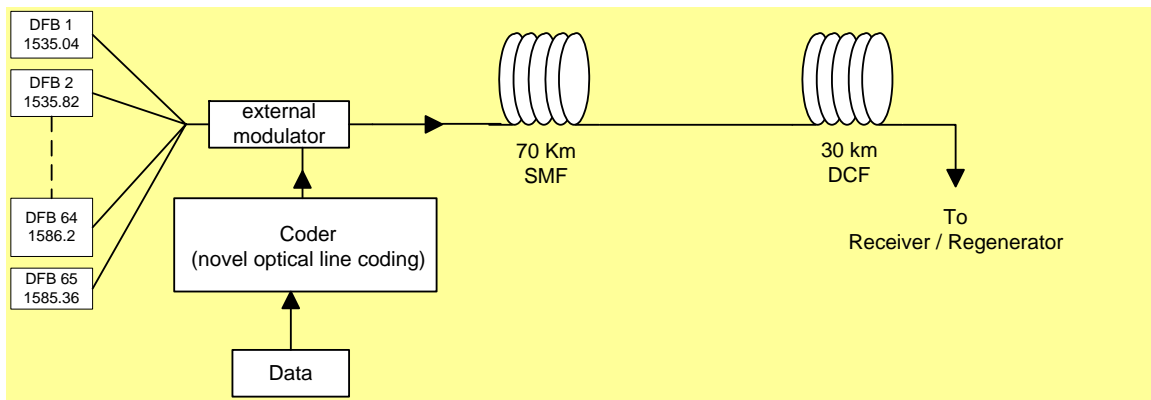


*Figure 30: Block diagram of the system*

The zero dispersion wavelength of the 70km-transmission SMF is 1300nm and its dispersion at 1550nm is 17ps/nm/km. Dispersion is compensated with a 30km dispersion compensated fiber, which has a dispersion of – 40ps/nm/km at 1550nm. Power spectrum of the WDM multiplexed carriers is given in Figure *Figure 31*.
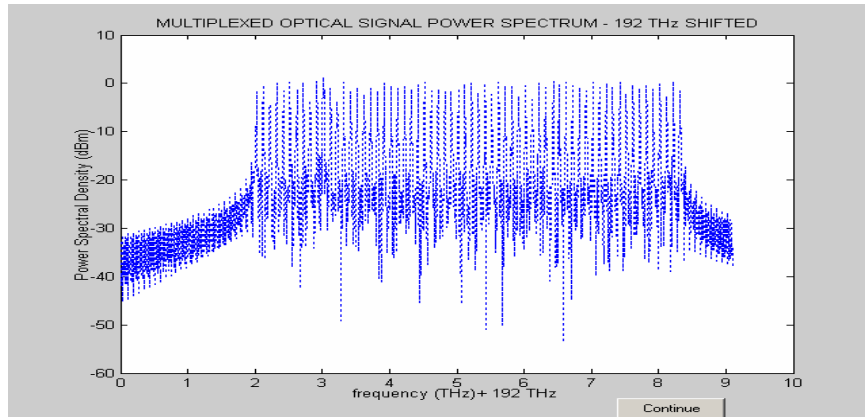
*Figure 31: Multiplexed power spectrum of modulated carriers*

Single clad fibber with material type E is used to design the DCF with 1.444 core index, 1.8294% delta and 2.6552μm diameter. The total dispersion is –40ps/nm/km at 1550nm. The characteristics of the designed DCF are shown in *Figure 32*.
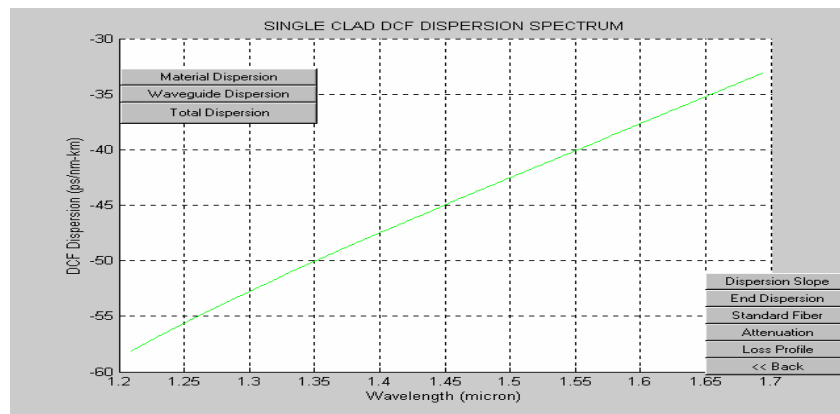


*Figure 32: Total dispersion of the DCF*

*Figure 33 Eye diagram after 100Km transmission (with dispersion compensation)*

Eye diagram after transmitting the multiplexed signal for 100Km along the SMF and DCF is shown Figure 33.

4.3　　50GHz spacing 40Gbit/s x 81 DWDM transmission over 100km dispersion managed fiber using carrier suppressed optical duo-binary Coding

The block diagram in *Figure 34* shown below demonstrates 3.24Tbit/s WDM transmission using 81 channel multiplexed 40Gbit/s duobinary coded signals over a 70 Km single mode fiber (SMF) and 30 Km of dispersion compensation fiber (DCF). Transmitted 81 channels are from 1535.04nm(195.30THz) to 1567.54nm(191.25THz) with 50GHz channel spacing.
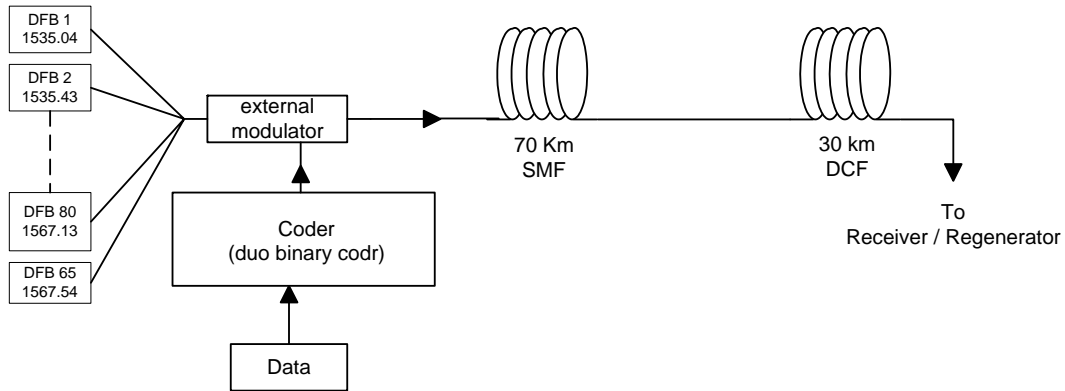
*Figure 34: Block diagram of the system*

The zero dispersion wavelength of the 70km-transmission SMF is 1300nm and its dispersion at 1550nm is 17ps/nm/km. Dispersion is compensated with a 30km dispersion compensated fiber, which has a dispersion of – 40ps/nm/km at 1550nm. Power spectrum of the WDM multiplexed carriers are given in *Figure 35*.
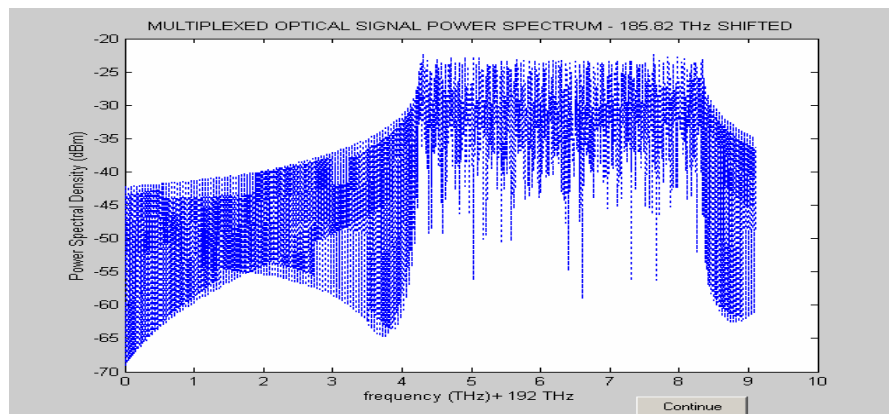


*Figure 35: Multiplexed power spectrum of modulated carriers*

Single clad fiber with material type E is used to design the DCF with 1.444 core index, 1.8294% delta and 2.6552μm diameter. The total dispersion is –40ps/nm/km at 1550nm. The characteristic of the designed DCF is shown *Figure 36*.
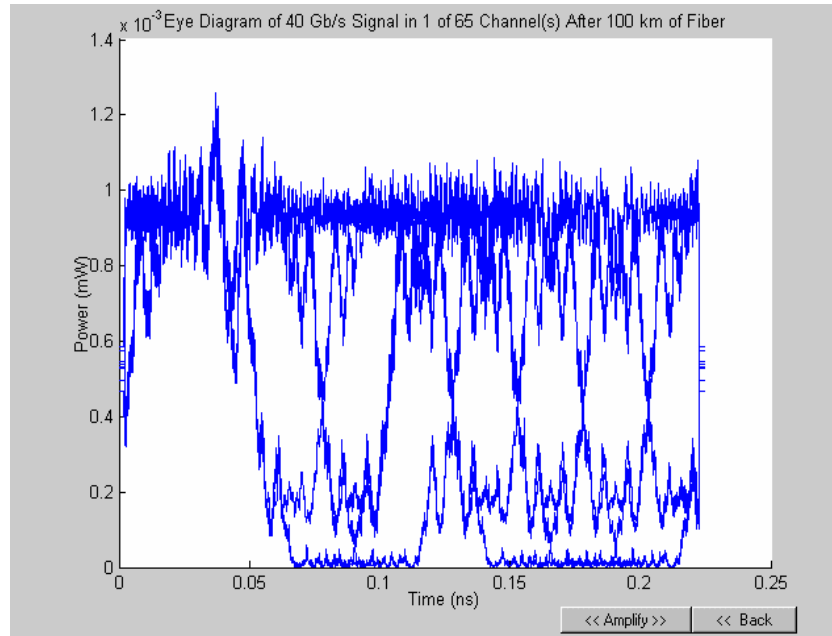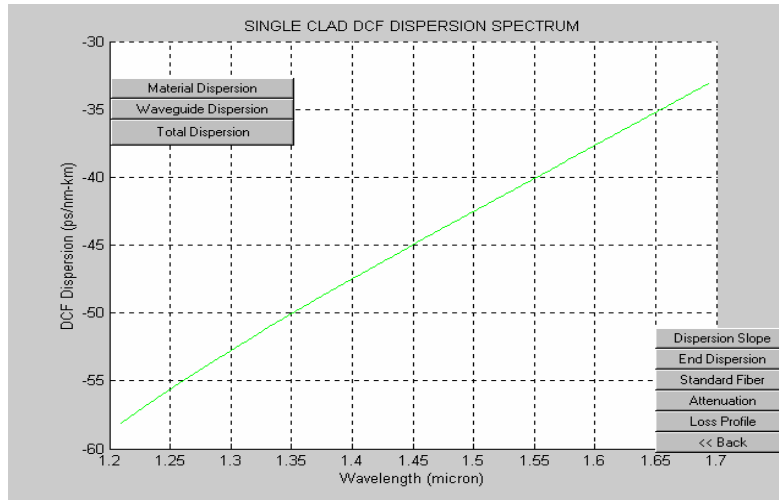
*Figure 36*: Total dispersion of the DCF

Eye diagram after transmitting the multiplexed signal for 100Km along the SMF and DCF is shown below.
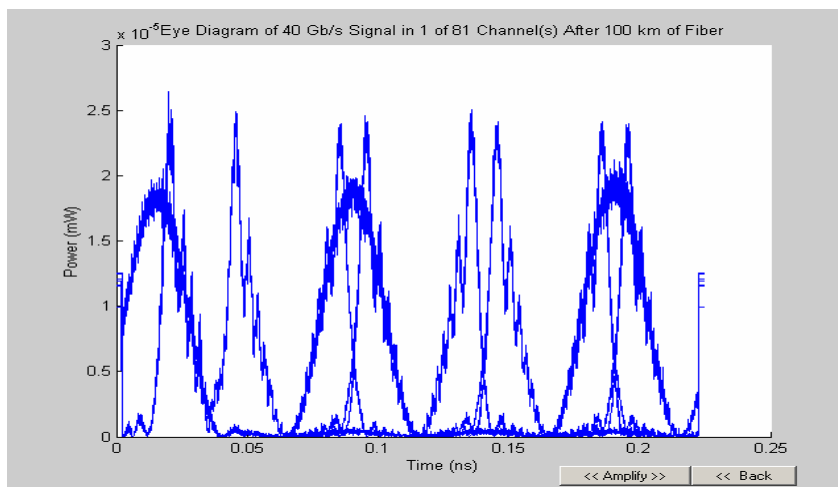


*Figure 37* Eye diagram after 100Km transmission (with dispersion compensation)

From the eye diagram of figure 30, it can be observed that there is a high frequency noise associate with the upper level of the eye diagram. Performance of the novel optical modulation format can be develop further by eliminating this noise by using a transmit filter

between encoder and the modulator. Ideal low pass filter is one of the best filters, immediately followed by a sixth order Butterworth type. At the presence of high dispersion this filter should have a sharp cutoff frequency [5].

5. CONCLUSIONS

This paper presents the implementation of the novel optical line coding technique (multi-level signaling) and carrier suppressed duo-binary-coding technique, in 40Gbit/s per channel long haul optical communication networks. Dispersion tolerance and the non linear tolerance measurement of those modulation formats were investigated, with number of case studies and comparing the simulation results with the performance of conventional RZ and NRZ modulation format in similar conditions. Finally the capability of using the interested modulation formats in DWDM multiplexed multi channel optical communication networks along the dispersion managed fiber optical links with 100Km amplifier/regenerator spacing is illustrated.

 From the simulation results indicate very clearly that dispersion tolerance of novel optical coding and optical duo-binary coding is superior to the conventional modulation techniques along the single mode fiber (without dispersion compensation). Initially (when the distance is less than about 11Km) duo-binary provide the best dispersion tolerance, but when the length increase further, novel optical coded signal becomes less dispersive.

When considering the non-linear tolerance, interested modulation techniques provided better results compared to the RZ and NRZ modulations. Up to the point where injected power is 15dBm both CS – duo-binary and novel optical coding perform equally well, however when the injected power is 20dBm first is better than the latter. This is mainly due to the low power

associated with the CS – duo-binary modulated signal due to the suppression of its carrier signal.

Section 6 provides the simulation results of N x 40Gbit/s DWDM transmission along a dispersion managed optical communication link with 100Km amplifier/regenerator spacing. With novel optical modulation 65 channels were transmitted with the spectral efficiency of 0.41 (bit/s)/Hz and in the case of CS – duo-binary modulation 81 channels were transmitted with the spectral efficiency of 0.8 (bit/s)/Hz. Higher spectral efficiency (with smaller channel spacing) could be achieved with duo-binary due to its reduced bandwidth.

Overall results of the paper illustrate the possibility of using multilevel signaling in designing modern advanced optical communication system of DWDM multiplexed *N x 40Gbit/s* channels with higher spectral efficiency and 100Km amplifier/regenerator spacing with a bit error rate (BER) less than $10^{-12}$.

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