Performance evaluation of high data rate transmission for microwave communication system over fiber link

A thesis submitted in partial fulfillment of the
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CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled, **“Performance evaluation of high data rate transmission for microwave communication system over fiber link”,** in partial fulfillment of the requirements for the award of degree of **Master in Engineering** in **Electronics & Communication Engineering** at **Thapar University,** Patiala, is an authentic record of my own work carried out under the supervision of **Dr. R. S. Kaler (Professor)** and refers other researcher’s work which are duly listed in the reference section.

The matter embodied in this thesis has not been submitted for the award of any other degree to any other university.

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ABSTRACT

The optical communication system has many advantages over conventional radio systems. The numbers of users of microwave communication are increasing day by day. But the bandwidth is limited for microwave transmission. The wide-bandwidth capability and very low attenuation in fibers of optical transmission systems makes them attractive for the transmission and processing of microwave signals. This strand has led to the development of the research area of microwave photonics. For transmitting microwave signal over fiber, there is a need to convert radio signal into optical form at the transmitter end and a reverse process at the receiver side. In this thesis, we have developed two types of techniques for transmitting radio frequency signal over fiber channel. First technique is based upon intensity modulation direct detection. In first technique, a laser is used to convert radio signal into optical signal. In the second, an external modulator (Mach–Zehnder modulator) with laser is used for the same purpose in the second technique (coherent system).

Firstly, the rate equation laser is operated in a dynamic state, where its intensity oscillates at a microwave frequency that varies with the input signal fed by wave generator. This system can also use for two modulating tones. The frequency of the first tone is varied from 1 to 20 GHz and second is set at 5 GHz. A data signal of 10 Gbps is transmitted over long haul single mode fiber by single tone system. A very good bit error rate (BER) 10 performances in a 100 Km and 25 Km fiber link is achieved for both single tone and two tones respectively in proposed microwave over fiber communication system.

Secondly, The Lorentzian laser is used with Mach–Zehnder modulator (MZM) to achieve a conversion of microwave band into baseband at which fiber operates. The key device in the coherent system is a Mach-Zehnder modulator which performs all-optical microwave mixing with semiconductor laser. The single pole low pass filter is realized by passing the microwave signals, acting as a dispersive device. An optically converted signal is obtained at the end of laser and this signal passes through a single mode fiber**.** In multi tone coherent system, the frequency of the first tone is varied from 1 to 20 GHz and second is set at 5 GHz. A data signal of 18 Gbps is transmitted over long haul single mode fiber by coherent system.

A soliton is a self-reinforcing solitary wave of permanent form which does not change its shape while travelling at constant speed. A dispersion compensated fiber and a periodical amplification is done to increase the efficiency of the soliton. To achieve a lossless soliton, the group velocity

dispersion (GVD) parameter is required to be constant along the fiber length. But it is difficult to achieve a constant GVD parameter, so dispersion compensated fiber is used for increasing the efficiency of the soliton fiber link. A circulating loop is used which is consist of three regular fiber spans, one dispersion-compensating fiber (DCF) span, optical filter and EDFA optical amplifier. The system transmits the data up to 9000 km. It is shown that the pulse spectrum is broadening due to the high-order soliton effect and third- order dispersion near the zero dispersion wavelength, the spectrum begin to be shaped by optical filter installed at the end of the loop. Thus the thesis investigates high data rate transmission for microwave communication system over fiber link.

CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

AFPM	Asymmetric Fabry–Perot modulator
ASE	Amplified spontaneous emission
BER	Bit error rate
BS	Base station
CD	Chromatic dispersion
CNR	Carrier-to-noise ratio
CS	Central stations
DCF	Dispersion compensated fiber
DFA	Doped fiber amplifier
DFB	Distributed feedback
EDFA	Erbium-doped fiber amplifiers
FWM	Four-wave mixing
GVD	Group velocity dispersion
HPT	Hetro-structure photo-transistor
IF	Intermediate frequency
IMDD	Intensity modulation/direct detection
ISI	Inter symbol interference
Lo	Local oscillator
MMIC	Microwave monolithic integrated circuit
MoF	Microwave over fiber
MQW	Multiple-quantum-well
MZM	Mach-Zehender Modulator
NZ-DSF	Nonzero dispersion shifted fibers
OFDM	Orthogonal frequency division multiplexing

PMD	Polarization-mode dispersion
QPSK	Quadrature phase-shift keying
RF	Radio frequency
RIN	Relative intensity noise
ROF	Radio over fiber
SBS	Stimulated Brillouin scattering
SLA	Semiconductor laser amplifier
SMF	Single-mode fibers
SNR	Signal-to-noise ratio
SOA	Semiconductor optical amplifier
SPM	Self-phase modulation
SRS	Stimulated Raman scattering
UTCPD	Uni-traveling-carrier photodiode
WDM	Wavelength-division multiplexing
WLAN	Wireless local area networks
XPM	Cross-phase modulation

LIST OF SYMBOLS

	Source power
μm	Micro meter
nm	Nano meter
	Lower Frequency
	Higher Frequency
P	Mean optical power
R	Photodiode responsivity
G	Fiber path gain
P	Laser output power
i	Modulating current
η	Modulation sensitivity
i	Laser bias current
β	Group velocity dispersion coefficient
γ	Self-phase modulation coefficient
T	Pulse width
z	Soliton period,
N	Soliton order
$\Delta\lambda$	Source line-width
D	Fiber dispersion
L	Fiber length
A(t)	Amplitude
ω	Angular frequency
A	Amplitude of local oscillater

ω	Angular frequency of oscilator
e	Electronic charge
B	Bandwidth of fiber

CHAPTER 1

INTRODUCTION

1.1 OPTICAL FIBER TRANSMISSION OF MICROWAVE SIGNALS

The research and development in optical fiber communication systems started around the first half of the 1970s. Due to high potential bandwidth and efficient transmission for long distances, optical fiber communication system has become the interested area in research [1]. The bandwidth can be used to transmit the radio signal after conversion of base band signal in to optical form. In Microwave over fiber (MoF) system, most of the signal processing (including switching, multiplexing, radio frequency (RF) generation, electrical- optical conversion, optical – electrical conversion & modulation etc) is made in central stations (CS) rather than in the base station (BS). So, this these systems make design of BS really simple [2].

The fiber band would be utilized to meet the requirement for broadband service and overcome the frequency congestion in the future wireless network [3]. Such systems used intensity modulation of semiconductor lasers, and the transmitted optical signal intensity was detected by a photodiode, which was regarded as a square-law detector. This combination of the transmitter and receiver is called the intensity modulation/direct detection (IMDD) scheme [4]. A new approach of coherent system is also employed in current optical communication systems. Coherent receivers could linearly down-convert the whole optical signal to a baseband electrical signal by using heterodyne or homodyne detection, and had the following advantages against direct detection:

(i) Different number of modes like Intensity, frequency, or phase modes can be used in coherent systems in spite of only intensity modulation as in case of IMDD scheme.

(ii) Coherent systems achieved excellent frequency selectivity by using electrical post-photo detector filters which is translated into the optical domain.

(iii) Shot-noise-limited reception can be achieved even at low received signal powers, simply by increasing the local oscillator (LO) power. The LO gives a signal gain, whereas the LO shot noise overwhelms the thermal noise of the receiver.

(iv) The coherent detection techniques are very useful in the realization of dense wavelength division multiplex schemes for multichannel transmission or single channel.

(v) The frequency resolution at the intermediate frequency (IF) or baseband stage is so high that we can separate closely spaced wavelength-division multiplexed (WDM) channels at the electrical stage.

(vi) The multilevel modulation format such as Quadrature phase-shift keying (QPSK) can be introduced into optical communications by using phase modulation [4].

The shot noise can be reduced by operating system at a wavelength of 1550 nm with effective optical amplifiers. However, there is interest in systems operating at 1300 nm wavelength in order to take advantage of the silica fiber dispersion minimum and the low noise and high output power of semiconductor-laser-pumped Nd-YAG lasers. There is also interest in systems operating at 850 nm wavelength for compatibility with GaAs microwave monolithic integrated circuit (MMIC) technology. Efficient optical fiber amplifiers are not available for either of these wavelengths. The alternative strategy for shot-noise-limited IMDD systems of increasing the source power is limited by the onset of stimulated Brillouin scattering (SBS) and other nonlinear effects in optical fiber [5].

1.2 TRANSMISSION IMPAIRMENTS

To build microwave over fiber communication systems, electrical and optical components are connected. In such a system, an electrical signal is converted into light signal which propagates from the transmitter to the receiver undergoes a number of impairments.

Attenuation

The fiber presents length and wavelength dependent optical attenuation. Beside the optical power loss caused by the components, the fiber further reduces the signal power. Figure 1.1 shows the attenuation loss of a fiber as a function of wavelength [6]. The peak in loss in the 1400 nm region is due to hydroxyl ion (OH^{--}) impurities in the fiber. In today's optical communications systems three wavelength bands are used: 0.85 μm, 1.3 μm, and 1.55 μm, where the latter band provides the smallest attenuation of ~ 0.25dB/km [7].

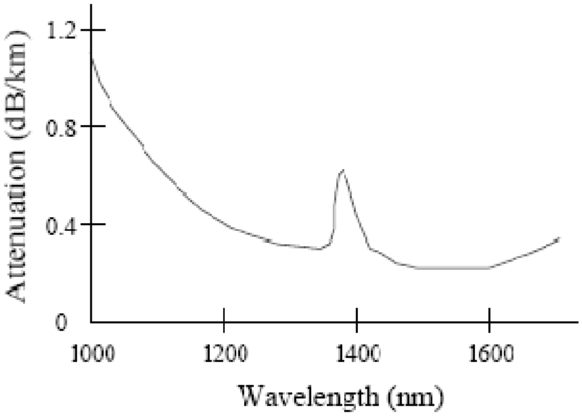


Figure 1.1 Attenuation of an optical fiber.

Dispersion

Dispersion may also affect the performance of the MoF link, specially, when the link lengths are very long. Dispersion is the name given to any effect wherein different components of the transmitted signal travel at different velocities in the fiber, arriving at different times at the receiver. As a result, the pulse widens and causes inter symbol interference (ISI). Thus, dispersion limits the minimum bit spacing, i.e., the maximum transmission rate. The amount of accumulated dispersion depends on the length of the link. The important forms of dispersion are modal dispersion, chromatic (material) dispersion, waveguide dispersion, and polarization-mode dispersion (PMD) [1].

Modal dispersion

Modal dispersion arises only in multimode fiber where different modes travel at different velocities. Clearly, in single-mode fibers modal dispersion is not a problem.

Waveguide dispersion

Waveguide dispersion is caused because the propagation of different wavelengths depends on waveguide characteristics such as indices and shape of the fiber core and cladding. After entering a single-mode fiber, information carrying light pulse is distributed between the core and the cladding. Its major portion travels within the core, the rest within the cladding. Both portions propagate at different velocities since the core and the cladding have different refractive indices [8].

Chromatic dispersion

Chromatic or material dispersion arises because different frequency components of a pulse (and also signals at different wavelengths) travel at different velocities due to the fact that the refractive index of the fiber is a function of the wavelength. It is typically measured in units of ps/nm.km, where ps refers to the time spread of the pulse, nm is the spectral width of the pulse, and km corresponds to the link length [7]. Typically, standard single-mode fibers (SMFs) have a chromatic dispersion of 17ps/nm.km at 1550 nm. Recently, so-called nonzero dispersion shifted fibers (NZ-DSFs) are installed more often. By controlling the waveguide dispersion accordingly, NZ-DSFs have a chromatic dispersion between 1 and 8 ps/nm.km, or between -1 and -8 ps/nm.km at 1550 nm [8].

Polarization-mode dispersion

PMD arises because the fiber core is not perfectly circular, particularly in older installations. Thus, different polarizations of the signal travel at different velocities. PMD is proving to be a serious impediment in very high-speed systems operating at 10Gbps and beyond [9].

Nonlinearities

As long as the optical power within an optical fiber is small, the fiber can be treated as a linear medium, i.e., the loss and refractive index of the fiber are independent of the signal power. However, when the power levels get fairly high in the system the nonlinearities can place significant limitations on high-speed MoF systems. Nonlinearities can be classified into two categories. The first set of effects occurs owing to the dependence of refractive index on the optical power. This category includes self-phase modulation (SPM), cross-phase modulation (CPM or XPM), and four-wave mixing (FWM) [10]. The second set of effects occurs owing to scattering effects in the fiber medium due to the interaction of light waves with phonons (molecular vibrations) in the silica medium. The two main effects in this category are stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS).

Self-phase modulation

SPM is caused by variations in the power of an optical signal and results in variations in the phase of the signal. SPM leads to the spectral broadening of pulses. Instantaneous variations in a signal’s phase caused by changes in the signal’s intensity will result in instantaneous variations of the frequency around the signal’s central frequency. For very short pulses, the additional frequency components generated by SPM combined with the effects of material dispersion also lead to spreading or compression of the pulse in the time domain, affecting the maximum bit rate and the bit error rate (BER).

Cross-phase modulation

XPM is a shift in the phase of a signal caused by the change in intensity of a signal propagating at a different wavelength. XPM can lead to asymmetric spectral broadening, and combined with SPM and dispersion, may also affect the pulse shape in the time domain [10].

Four-wave mixing

FWM occurs when two wavelengths, operating at frequencies f_1 and f_2, respectively, mix to cause signals at frequencies such as $2f_1 - f_2$ and $2f_2 - f_1$. These extra signals can cause interference if they overlap with frequencies used for data transmission. Similarly, mixing can occur between combinations of three and more wavelengths [7].

Stimulated Raman scattering

SRS is caused by the interaction of light with molecular vibrations. Light incident on the molecules creates scattered light at a longer wavelength than that of the incident light. A portion of the light traveling at each frequency is downshifted across a region of lower frequencies. The light generated at the lower frequencies is called the Stokes wave. The fraction of power transferred to the Stokes wave grows rapidly as the power of the input signal is increased. In multi wavelength systems, the shorter-wavelength channels will lose some power to the higher-wavelength channels. To reduce the amount of loss, the power on each channel needs to be below a certain level [1].

Stimulated Brillouin scattering

SBS is similar to SRS, except that the frequency shift is caused by sound waves rather than molecular vibrations. Other characteristics of SBS are that the Stokes wave propagates in the opposite direction of the input light. The intensity of the scattered light is much greater in SBS than in SRS, but the frequency range of SBS is much lower than that of SRS. To counter the effects of SBS, one must ensure that the input power is below a certain threshold. Also, in multi wavelength systems, SBS may induce crosstalk between channels. Crosstalk occurs when two counter propagating channels differ in frequency by the Brillouin shift, which is around 11 GHz for wavelengths at 1550 nm [8].

Crosstalk

Crosstalk decreases the signal-to-noise ratio (SNR) leading to an increased BER. Crosstalk may either be caused by signals on different wavelengths (inter channel crosstalk) or by signals on the same wavelength on another fiber (intra channel crosstalk) due to imperfect transmission characteristics of components. Inter channel crosstalk must be considered when determining channel spacing. In some cases, inter channel crosstalk may be removed through the use of appropriate narrowband filters. Intra channel crosstalk usually occurs in switching/routing nodes where multiple signals on the same wavelength are being switched/routed from different inputs to different outputs. This form of crosstalk is more of a concern than inter channel crosstalk because intra channel crosstalk cannot be removed through filtering [10].

Noise

The SNR is deteriorated by different noise terms. In particular, we consider amplified spontaneous emission (ASE) of optical Erbium-doped fiber amplifiers (EDFAs), shot noise of photodetectors, and thermal noise of electrical amplifiers [11].

Amplified spontaneous emission

An optical EDFA amplifies an incoming light signal by means of stimulated emission. Besides stimulated emission also spontaneous emission takes place which has a deleterious effect on the system. The amplifier treats spontaneous emission radiation as another input signal and the spontaneous emission is amplified in addition to the incident light signal. The resulting ASE appears as noise at the output of the EDFA [12].

Shot noise

A photo detector converts the optical signal into an electrical photocurrent. The main complication in recovering the transmitted bit is that in addition to the photocurrent there is a shot noise current. Shot noise current occurs due to the random distribution of the electrons generated by the photo detection process even when the input light intensity is constant. (Note that the shot noise current is not added to the generated photocurrent but is merely a convenient representation of the variability in the generated photocurrent as a separate component.)

Thermal noise

Since the photocurrent is rather small it is subsequently amplified by an electrical amplifier. This electrical amplifier introduces an additional thermal noise current due to the random motion of electrons that is always present at typical temperatures.

1.3 IMDD MoF SYSTEM

The basic approach to optical signal modulation and recovery is based upon intensity modulation direct detection technique (IMDD). A schematic diagram of IMDD is shown in figure 1.2. Signal source is used to generate the electrical signal. This signal is converted in to optical domain with the help of laser source. This signal is transmitted through the fiber. Due to long distance travelling of signal, EDFA amplifiers at both sides of the channels are used to maintain the signal strength.

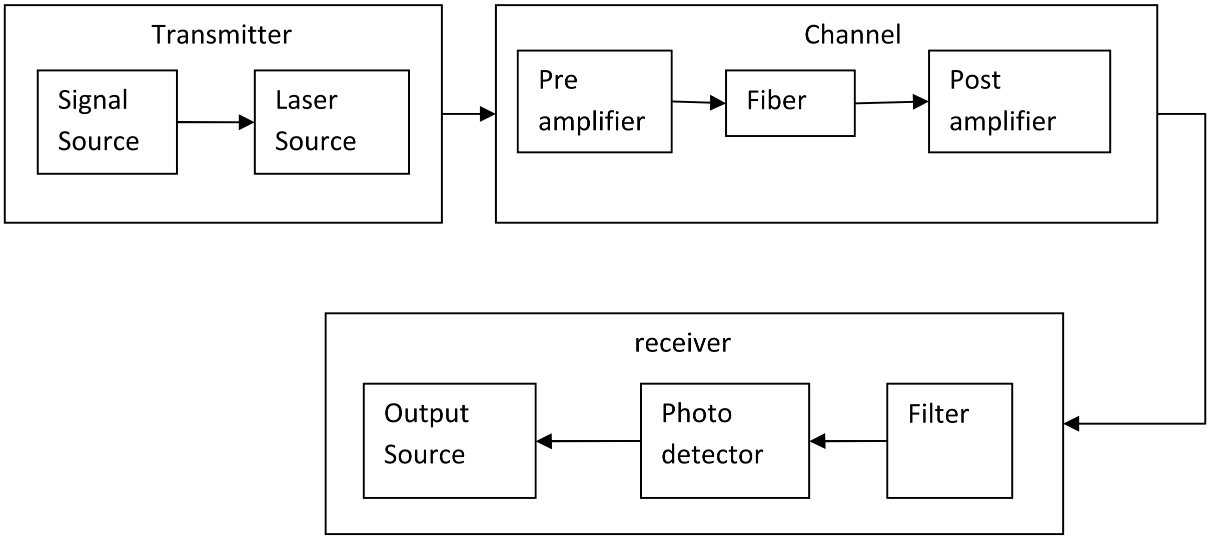


Figure 1.2 IMDD transmission system

The noise is produce due to channel distortion and amplifiers, so filter is used to remove the noise. Photo-detector is used to detect the optical signal and to convert the signal in to microwave frequency.

Let the microwave signal to be transmitted be represented by s(t). The optical power at the output of the intensity modulator is

$$= \quad (1 + \quad (\ ))$$

Where is the mean optical power and k is the modulation sensitivity (k s(t)> -1). The mean squared signal current at the detector output is

$$= (\qquad) | \quad |$$

Where R is the photodiode responsivity and G is the fiber path gain (G will be always less than one unless optical amplifiers are used). Various types of Noise arise at the detector output from several sources like thermal noise and shot noise current generated in the photodiode load, optical source relative intensity noise and noise generated by any optical amplifiers [3]. The diode dark current and optical amplifier contribution is very small and can be assumed negligible.

If we have optical power below the relative intensity noise (RIN) (so that shot noise limited reception can be achieved and thermal and source relative intensity noise also can be limited), then we have a improved signal to noise ratio (SNR) [13].

The SNR at the detector output can be taken as

$$\mathrm{SNR} = \frac{(\qquad)}{\qquad}$$

Where e is the electronic charge and B is the bandwidth.

The alternative strategy for shot-noise-limited IMDD systems of increasing the source power Po is limited by the onset of stimulated Brillouin scattering (SBS) and other nonlinear effects in optical fiber [5].

1.4 COHERENT MoF SYSTEM

Figure 1.3 shows the basic concept of coherent MoF system. Electrical signal generator is used to generate electrical signal. This signal is then modulated with the help of external modulator. A signal from laser source is also fed to the input of external modulator. Both signals are combined and send to the channel. At the channel fiber is used as transmitting media, EDFA amplifiers are also used in channel for long distance transmission. At receiver side, the incoming signal is detected linearly with the homodyne receiver, comprising phase and polarization diversities [3].

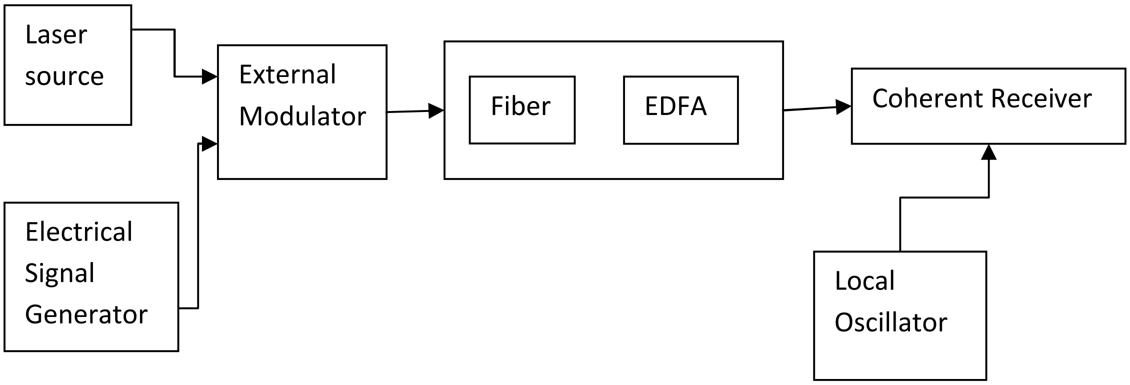


Figure 1.3 Coherent MoF system

1.5 COMPONENT FOR OPTICAL TRANSMISSION OF MICROWAVE SIGNALS

Output wavelength, output power, intensity noise, modulation response are the key performance parameters for directly modulated sources. The main optical sources are fiber lasers, crystal and waveguide lasers, and semiconductor lasers. Only semiconductor lasers offer direct modulation capability [3].

Fiber Laser: The use of optically pumped fiber doped with an appropriate lasing ion has made a key contribution to optical communication through the optical fiber amplifier. The required doped fiber length depends on cavity losses, pump power, and lasing ion doping concentration. The latter is limited by clustering, so that practical erbium-doped fiber lasers for operation at 1530 nm wavelength typically require doped fiber lengths of 1-5 m, giving laser mode separations of 100-20MHz [14].

Crystal and Waveguide Lasers: Diode-pumped crystal lasers are attractive sources of high-power (>100mW), narrow line-width (<1 GHz), low RIN (<−170 dBc/Hz) optical signals [15]. They offer superior amplitude and phase noise characteristics to those available from semiconductor designs due to the slow gain dynamics of the active rare earth ions. The most successful designs are based on the 1320 nm wavelength transition in Nd:YAG and the 1530 −1550 nm wavelength range transitions in Er: Glass. They are finding application as sources in wide dynamic range direct detection analog optical transmission systems for cable TV and related applications [16]. For general application, they suffer from limited tunability (<60GHz) and high optical complexity. Improved optical confinement and potential for integration with other optical and electro-optic components make rare-earth-doped waveguide lasers of interest. Non-semiconductor waveguide lasers require an optical pump source, which is generally desired to be a diode laser. Thus a fully integrated source technology is not possible.

Semiconductor lasers: These are mostly used as sources in current optical communication systems. They offer the advantages of direct electrical pumping and modulation capability.

At frequencies below the photon-electron resonance, the modulation response is uniform and given by

$$= \eta$$

Where the modulated component of the laser output power; the modulating current, and η is the modulation sensitivity [3]. This modulation sensitivity can be defined as

$$= \frac{}{}$$

Where is the laser bias current. So by maximizing η we can minimizes the transmission system losses in IMDD systems. The simplicity of direct modulation of semiconductor lasers has proved attractive for many applications, and following early work on modulation characteristics, rapid progress has been made in reducing electrical parasitic of laser structures and optimizing laser parameters for high-speed operation [17]. The introduction of multiple-quantum-well (MQW) active regions led to considerable reductions in threshold current and an increase in differential gain by up to a factor of 2 relative to bulk devices [18]. Multi-section distributed feedback (DFB) lasers have been realized with tuning ranges of 10 nm, while maintaining linewidths less than 20 MHz [19]. Wider tuning ranges have been achieved in vertically coupled structures [20].

For coherent analog optical transmission systems generally require tunability for source/LO laser wavelength matching and channel selection, uniform FM frequency response for optical FM and phase-locked applications, and narrow line-width for high SNR in angle-modulated systems.

More recently, monolithically integrated sources using the same technique have been realized in GaAs/AlGaAs [21] systems. Careful design of semiconductor laser structures to minimize spatial hole burning effects has led to the realization of MQW DFB lasers having line-widths below 100 GHz, a value sufficiently small to permit high SNRs in angle modulated systems [22]

Optical Amplifiers: Gain, the optical amplifier parameter, need to be greater than unity. So, different developments are done to realize the amplifiers having gain greater than unity. They can also be used to compensate for splitting losses in multipoint distribution systems. The most important optical amplifier technologies for microwave signal transmission applications are the traveling wave semiconductor laser amplifier (SLA) [23] and the doped fiber amplifier (DFA) [24]. When the modulation frequency is greater than the reciprocal of the carrier lifetime, typically 2 ns, the distortion is seen to be small. This restricts the minimum intensity modulation frequency to several GHz, making them unsuitable for a number of wireless system applications, such as cellular radio signal distribution. The EDFA is pumped using a semiconductor laser and has the advantage that it can be spliced directly into a fiber system, avoiding significant coupling losses. Since the fluorescence lifetime of erbium is long (>10 ms), low distortion performance can be maintained for modulation frequencies down to the GHz region [25].

Photodetectors: For microwave signal transmission, depletion layer photodetectors are preferred for their speed and good quantum efficiency. For such devices, 3 dB bandwidths in excess of 100 GHz were demonstrated some years ago [26]. In high dynamic range microwave photonic systems, detector power handling and nonlinear effects are of great importance. The effect of the generated carriers on the electric field within the detector is an important limiting factor [27-28]. The combination of thin depletion regions and doped absorbers is used for increasing efficiency. Other devices utilizing doped rather than fully depleted absorbers include the uni-traveling-carrier photodiode (UTCPD) [29]. Thin depletion regions are the key to obtaining high photocurrent for two reasons. First, since most photodiodes fail because of high thermal dissipation, the thin depletion region can attain higher electric fields for the same applied voltages, thus lowering Joule heating. Second, the space-charge effect is reduced because the space-charge-field is proportional to the number and separation of carriers within the depletion region, which are both reduced because of the short transit time. While doped absorber photodiode designs can offer operation at frequencies into the THz band [30], excessive minority electron transit time can lead to additional small nonlinearities including current-dependent bandwidth, nonlinear responsivity, and harmonic distortion [31].

The main design challenges for photodiodes in microwave transmission systems are to achieve wide bandwidth, high linearity, and high quantum efficiency, without compromising the optical power handling requirements for shot-noise limited systems. Amongst other photo-detector technologies, the most exciting for microwave applications, due to its internal current gain, is the hetro-structure photo-transistor (HPT) [3].

External modulators: An external modulator is desired in coherent systems to avoid transmission system gain limitation due to limited source modulation sensitivity which is a problem in direct detection. For a Mach−Zehnder interferometric modulator operated well within its bandwidth, the modulation response is uniform [32]. These modulators operate by converting the incident light into photocurrent in their absorbing state. Bulk modulators at 1530 nm wavelength have achieved -3 dB electrical bandwidths of 50 GHz with 3.5V drive for 20 dB extinction and fiber-to-fiber insertion loss of about 8 dB [33]. Coupling losses between optical fiber and semiconductor waveguide modulators can be reduced by moving to non-waveguide reflective modulator designs in which the light is incident perpendicular to the junction plane, as in the asymmetric Fabry-Perot modulator (AFPM). In common with other electro-absorption modulators, these devices can also be used as detectors to create a duplex system [34].

Optical Amplifiers: The development of optical amplifiers has made it possible to realize systems in which the signal gain is greater than unity. They can also be used to compensate for splitting losses in multipoint distribution systems. The most important optical amplifier technologies for microwave signal transmission applications are the traveling wave semiconductor laser amplifier (SLA) [35] and the doped fiber amplifier (DFA) [24].

1.6 DISPERSION MANAGED SOLITON

A soliton is a self-reinforcing solitary wave of permanent form which does not change its shape while travelling at constant speed. These waves are caused by a cancellation of nonlinear effects of medium. The frequency and the speed of the waves also affect the behavior of the soliton. The first phenomenon about soliton was given by John Scott Russell who observed a solitary wave in the Union Canal in Scotland. He reproduced the phenomenon in a wave tank and named it the "Wave of Translation" [36].

Soliton communication systems are leading candidates for long-haul light wave transmission links. One normally thinks of the soliton as involving dynamic balance along its path between the dispersive and nonlinear terms of the non-linear Schrodinger equation [37]. The ideal soliton can exist in a lossless fiber with a balance between the chirp induced by fiber group velocity dispersion (GVD) and fiber nonlinearity characterized by self-phase modulation (SPM) [38]. Dispersion and non-linearity can interact to produce permanent and localized wave forms. Consider a pulse of light traveling in glass. This pulse can be thought of as consisting of light of several different frequencies. Since glass shows dispersion, these different frequencies will travel at different speeds and the shape of the pulse will therefore change over time [39].

For a long-haul soliton communication system, the amplification process is accompanied by the emission of spontaneous noise. With the help of filter, the noise that is outside the bandwidth of the optical signal can be removed. But the noise present inside is difficult to remove. The noise added to the signal by each amplifier induces an uncertainty in the soliton arrival time called jitter. Gordon and Haus showed that the statistics of the jitter due to spontaneous emission noise added by the lumped amplifiers is Gaussian with a variance proportional to the cube of the total distance of the links [40].

The existence of solitons in optical fibers is the result of a balance between the chirps induced by fiber dispersion characterized by GVD (group velocity dispersion) coefficient and fiber nonlinearity characterized by SPM (self-phase modulation) coefficient γ [41]. For long-distance optical transmission systems, optical amplifiers must be used to compensate for fiber loss. Stimulated Raman scattering (SRS) in optical fiber is promising for soliton transmission since it operates as a distributed gain medium [42].

Analytically soliton is a solution of nonlinear Schrodinger equation describing pulse propagation in optical fiber and can be derived as:

$$S(t) = N \quad \overline{}\ \mathrm{sech} - \exp(\quad \Pi \frac{}{})$$

Where - soliton peak power, *T* - pulse width, - soliton period, and *N* - soliton order. The optical pulse which corresponds to N=1 is called fundamental soliton. Pulses with N>1 are called higher-order solitons [41]. Soliton order parameter N depends on the balance between dispersion and nonlinearity and is defined as:

$$= \frac{}{} = \frac{}{|\quad|}$$

1.7 ADVANTAGES OF MoF SYSTEM

Low Attenuation Loss

Electrical distribution of high frequency microwave signals is problematic. The transmission lines are not noise free and also impedance rises with frequency. In free space, losses due to absorption and reflection increase with frequency.

Enormous Bandwidth

Optical fibers offer enormous band width. The three main transmission windows, which offer low attenuation, are 850nm, 1310nm and 1550nm wavelengths. The availability of low dispersion (dispersion shifted or dispersion flattened) fiber, EDFA are the main factors to increase the bandwidth capacity of the fiber.

Cross Talk

Optical fiber is immune to electromagnetic transmission. This is so because signals are transmitted in the form of light through the fiber. So, a noise free transmission of microwave signal for long distance is possible through a fiber.

Less Complexity

In microwave communication system, numbers of antennas are used. Frequency conversion is also main problem with microwave transmission system. The size of the fiber is as thin as human hair, so the system complexity is reduced. Easy installation and low maintenance costs of fibers are also very important advantage for MoF systems.

Low Cost

The fiber has a very low cost. The installation of fiber communication system is also low as compare with microwave antenna system. Also, the maintenance cost of fiber is almost zero.

CHAPTER 2

LITERATURE SURVEY

2.1 MICROWAVE OVER FIBER COMMUNICATION SYSTEM

L.Chen et al. [3] demonstrated a wavelength reuse scheme for up-link connection in a radio over-fiber (RoF) system with photonics generated 2.5 Gbit⁄s 16QAM OFDM signals. The 2.5 Gbit⁄s 16QAM OFDM signals were carried by the optical millimeter-wave (mm-wave) carriers which were generated with four times frequency of the local oscillator (LO) signal. The power penalties for both down- and up-stream signal deliveries over 20 km fiber were less than 1 dB.

M. Garcia Larrode et al. [34] demonstrated the optical frequency multiplication method. The modal bandwidth limitation of an MMF link is studied in RoF systems. The experiments studied the generation of microwave carriers up to 40 GHz and distribution them over 4.4 km of MMF link. Also, 16-QAM and 64-QAM radio signals were up converted from 300 MHz to 23.7 GHz and 29.7 GHz, and recovered successfully after the MMF link. Results suggested that the system performance was not jeopardized by modal dispersion, and that any length of MMF could be used. The RF bandwidth limit of the link was determined by the distance between generated harmonics, i.e., the sweep frequency, which was an adjustable system parameter.

Hai-Han Lu et al. [43] proposed a full-duplex ROF transport system based on main and multiple side modes injection-locked DFB LD. The practicability of ROF systems with WIMAX data stream achieved and good BER performance over a 120 km SMF links for both down/uplinks was investigated. The experimental results showed that the proposed system was applicable for long-haul full-duplex microwave optical links. A data signal of 70 Mbps/10 GHz (WiMAX) signal was transmitted over long-haul single-mode fiber (SMF) transmission.

M. T. Zhou et al. [44] demonstrated full-duplex RoF transmission of 1.25-Gigabit Ethernet signal on 60-GHz band subcarrier. By using a simple and low-cost all-fiber optical inter leaver fabricated, the downlink performance was improved and the downlink optical carrier was recovered for uplink reuse.

Sze Chun Chan et al. [45] demonstrated optical conversion from an OC-12 622-Mbps AM baseband signal to the corresponding FM microwave signal. The microwave was centered at 15.90 GHz. A bit-error rate of less than 10−9 was measured. The demonstration was restricted by the bandwidths of the detection electronics, but the optical injection system itself was capable of high frequency operation with a very large bandwidth. By varying the optical injection strength or the detuning frequency, the microwave frequency varied from 10 GHz to at least 100 GHz. A maximum frequency deviation of more than 10 GHz was achieved. The system was also be applied for generating a frequency-hop spread spectrum when the injection strength switched among multiple levels.

Paul Goldgeier et al. [46] described long-distance analog microwave-fiber optic links with bandwidths larger than six and a half octaves at an upper frequency in the 1.5–2 GHz range**.** The links exhibited highly linear performance with harmonic and inter-modulation distortions determining the overall spurious-free dynamic ranges. Two configurations were presented, each capable of overcoming limitations imposed by fiber nonlinearities and each employing a custom optical amplifier which maintains a low-noise figure under saturated conditions. The noise figure 38 dB obtained with a fiber loss of 14 dB over a six and a half octave bandwidth at an upper frequency of 2 GHz. The dynamic ranges were limited by the lack of a highly linear low-noise electronic preamplifier.

J. He et al. [47] experimentally demonstrated two schemes of full duplex Radio over fiber (ROF) systems with frequency-quadrupled optical millimeter-wave generation and wavelength reuse for uplink connection. In the two schemes, as a MZM driven by an RF at 10 GHz, 40 GHz millimeter-wave was generated, which can greatly reduce the bandwidth of microwave, component and modulator. Two schemes, A & B, considering the impact of fiber chromatic dispersion were also compared. For scheme A, the millimeter-wave with frequency quadruple was generated only by one MZM. But in this system, the millimeter-wave power fluctuated due to constructive and destructive interaction between the two beatings induced by chromatic dispersion. For scheme B, only the generated millimeter-wave was modulated by downstream data, the optical carrier was not. So the upstream data carried by the optical carrier had better performance.

K. Blary et al. [48] tested a digital optical switch for analogue signal applications. Electrical properties of detected switched RF signal have been investigated. The judicious choice of the material constituting the optical waveguide core, i.e. with a cut-off wavelength near to the working one, allowed one to reach high electrical on/off ratios, i.e. -55 dB. No electrical additive phase noise had been pointed out relative to the optical switching operation.

Fei zeng et al. [60] proposed and demonstrated an all-optical signal processor that performed both microwave mixing and band pass filtering in a radio-over-fiber link. The key device in the processor was an electro-optic phase modulator which performs all-optical microwave mixing. An up- or down-converted microwave signal was obtained and other unwanted frequency components are rejected at the end of the fiber span. The use of the proposed signal processor to perform an up-conversion of a microwave signal from 3 to 11.8 GHz in a 25-km fiber link was demonstrated.

2.2 DISPERSION COMPENSATED SOLITON TRANSMISSION

John Scott Russell et al. [36] described the wave of translation. The motion of a boat which was rapidly drawn along a narrow channel by a pair of horses was observed. The first idea about the soliton was given in this. The soliton waves, their properties and comparison of these waves with normal sea waves were investigated. They stated that unlike normal waves the soliton waves never merge and the speed depends on the size of the wave, and its width on the depth of water.

Masataka Nakazawa et al. [41] showed that propagation of a non transform-limited (chirped) pulse at a wavelength that was slightly shifted into the anomalous dispersion region. The quasi-steady-state chirped pulse was generated by balancing the chirp in the anomalous region that accompanied the nonlinear phase change with that in the normal region. This mechanism was similar to the dispersion allocated soliton and the stretched pulse mode-locking techniques.

E. Kengne et al. [49] demonstrated a class of dissipative complex Ginzburg–Landau (DCGL) equations that govern the wave propagation in dissipative nonlinear transmission lines. Two-soliton solutions of the DCGL equations, from which the one-soliton solutions was deduced and obtained in analytical form. The modified Hirota method imposed some restrictions on the coefficients equations. The physical requirement of the solutions imposed complementary conditions on the combination of the dispersion and nonlinear gain/loss terms of the equation, as well as on the coefficient of the Kerr nonlinearity. The analytical solutions for one solitary pulse were tested in direct simulations.

Hirokazu Kubota et al. [50] presented new soliton transmission method with lumped amplifiers. A new possibility for long-distance soliton propagation with the pre-emphasis method was shown. For a given amplifier spacing, by increasing the input pulse intensity up to a maximum of 1.4, the pre-emphasis method was very successful in sending solitons over long distances.

M. Kumar et al. [51] investigated the performance of first- and second-order path-averaged soliton long-haul transmission link. The impact of third-order dispersion (TOD) at varied chirp has been discussed. The observations established that the pulse width (FWHM) remains within the optimal range without and up to certain discrete values of the chirp factor.

Linn F. Mollenauer et al. [52] showed both analytically and with numerical simulation, that solitons were remarkably resilient to large variations in energy and dispersion, as long as the characteristic length scale of those variations was considerably less than . There was therefore no barrier to the use of lumped amplifiers, nor to the use of practical dispersion shifted fibers, in ultra-long distance communication using solitons.

M. Nakazawa et al. [53] presented a technique to reduce the interaction forces between adjacent solitons. Soliton data transmission at 7.2-10Gbit/s over one million kilometres had been successfully achieved. Synchronous shaping and retiming using a high speed optical modulator was also achieved. The accumulation of amplified spontaneous emission and the effect of interaction forces between adjacent solitons were overcome. This technique was analogous to the synchronously pumped laser technique and extended the soliton transmission distance almost infinitely.

M. Nakazawa et al. [54] described a bright optical soliton by a nonlinear Scbrodinger equation which survived in a positive dispersion region. The fibers with large positive and large negative dispersion were combined, which introduced solitons in a commercial system. The repeater spacing was extended through this technique.

Jianjun Yu et al. [55] optimized dispersion-allocated fiber in order to realize long amplifier spacing, long distance soliton transmission. Dispersion-decreasing-allocated fiber was used to transmit stable soliton over long distance. In order to realize soliton bidirectional transmission, symmetrical configuration of the dispersion-allocated fiber within an amplifier spacing was designed.

C. Masood Khalique et al. [56] obtained the 1-soliton solution of the NLSE in various forms of non-Kerr law media. The approach that was used to obtain the soliton solution is the Lie symmetry analysis approach. The Lie point symmetry analysis of the corresponding eigen value problem was carried out. Subsequently, using the canonical transformations and invariants, the corresponding soliton solution can be simply obtained by quadratures.

2.3 MOTIVATION

Optical fiber is established as the medium of choice for high-capacity long haul digital transmission systems and is moving rapidly into the access area. Its use in high-speed local area networks is also widespread. A less well-known application area of MoF is its use for the transmission of microwave signals for cable television, cellular radio, wireless local area networks (WLAN), and microwave antenna remoting. Many papers advocating MoF for high data rate transmission in the research literature have been qualitative. The Recently, MoF Technology has been studied to enhance the wireless transmission. Various approaches have been suggested for enhancing the higher bit rate but till now experiments are limited to short distance and have a very low bit rate data transmission. Also, all the papers are related to single tone data transmission. For the transmission of data in various formats, multi tone system is required. Also, multipath fading and nonlinear intensity modulation degraded the microwave signal. Solitons theory and wave behavior have been qualitative in number of research papers. But, there is loss due to non linearity and dispersion in Soliton. In soliton transmission, there are two serious problems. The first is related to the selection of fibers which have specified negative group velocity dispersion (GVD). This results in a low yield in terms of fiber fabrication. The second problem is that the amplifier spacing ***L,*** cannot be extended as far as that in conventional systems

2.4 OBJECTIVES OF THESIS

1. To implement single tone and multi tone microwave over fiber link system using intensity modulation direct detection method.
2. To achieve a high data rate transmission for microwave over fiber communication system using coherent method for both single tone and multi tone.
3. To increase the efficiency of soliton transmission system by minimizing the losses and dispersion in fiber link.

2.5 THESIS ORGANISATION

This thesis is divided into six chapters. The first chapter describes the concept and evaluation of microwave over fiber communication system using direct detection method and coherent system. Various transmission impairments and dispersion managed soliton transmission system also described in the first chapter.

The second chapter includes the literature survey of microwave over fiber communication system and dispersion managed soliton transmission.

The third chapter describes the MoF system using direct detection method. An intensity modulation direct detection technique is used to convert microwave signal in to optical signal. The rate equation laser is operated in a dynamic state, where its intensity oscillates at a microwave frequency that varies with the input signal fed by wave generator. This system can also use for two modulating tones.

In the fourth chapter, another technique, coherent system is described. In this technique, a Mach–Zehnder modulator (MZM) is used to generate millimeter-wave using optical frequency and signal modulation. This system has many advantages over conventional direct detection method.

The fifth chapter analyzed the loss less dispersion soliton transmission system. A dispersion compensated fiber is used to manage the dispersion value in channel.

Finally the sixth chapter includes conclusion and future scope of work.

CHAPTER 3

SINGLE TONE AND MULTI TONE MICROWAVE OVER FIBER COMMUNICATION SYSTEM USING DIRECT DETECTION METHOD

An analog microwave over fiber link for long haul distance based upon Rate Equation Laser is demonstrated. This system uses the advantage of high potential bandwidth of fiber in transmission of microwave signal. The interface of the two systems needs an up-conversion of microwave band into baseband (at which fiber operates). An intensity modulation direct detection technique is used to achieve this purpose. The rate equation laser is operated in a dynamic state, where its intensity oscillates at a microwave frequency that varies with the input signal fed by wave generator. This system can also use for two modulating tones. The frequency of the first tone is varied from 1 to 20 GHz and second is set at 5 GHz. A data signal of 10 Gbps is transmitted over long haul single mode fiber by single tone system. A very good bit error rate (BER) 10 performances in a 100 Km and 25 Km fiber link is achieved for both single tone and two tones respectively in proposed microwave over fiber communication system.

3.1 INTRODUCTION

The use of microwave over fiber link (MoF) for distributing microwave signals has attracted much attention in the last few years [57]. Research efforts have been mainly dedicated to enhance baseband digital transmission performance fibers link [58], as well as to develop low-cost microwave-over-fiber techniques for long haul distances [59]. A less well-known application area of MoF is its use for the transmission of microwave signals for cable television, cellular radio, wireless local area networks (WLAN), and microwave antenna remoting [3]. In a MoF system, optical fibers are used to connect the central office to remote base stations, where carrying microwave subcarriers are transmitted. Photo-detectors are applied to recover the microwave signals at the base stations, which are then radiated to the wireless customer units. MoF has the advantages of centralizing the high-speed data transmission in the central office and allowing effective long-distance microwave transmission with a better efficiency. Semiconductor laser sources for MoF include directly modulated lasers, rate equation lasers, multi-section lasers, and optically injected lasers [45].

Paul Goldgeier et al. [46] described long-distance analog microwave-fiber optic links with bandwidths larger than six and a half octaves at an upper frequency in the 1.5–2 GHz range**.** The links exhibited highly linear performance with harmonic and inter-modulation distortions determining the overall spurious-free dynamic ranges. Two configurations were presented, each capable of overcoming limitations imposed by fiber nonlinearities and each employing a custom optical amplifier which maintains a low-noise figure under saturated conditions.

Sze Chun Chan et al. [45] demonstrated optical conversion from an OC-12 622-Mbps AM baseband signal to the corresponding FM microwave signal. The microwave was centered at 15.90 GHz. A bit-error rate of less than 10−9 was measured.

L.Chen et al. [3] demonstrated a wavelength reuse scheme for up-link connection in a radio over-fiber (RoF) system with photonics generated 2.5 Gbit⁄s 16QAM OFDM signals. A 2.5 Gbit⁄s 16QAM OFDM signals by the optical millimeter-wave (mm-wave) carriers were generated with four times frequency of the local oscillator (LO) signal. The power penalties for both down- and up-stream signal deliveries over 20 km fiber were less than 1 dB.

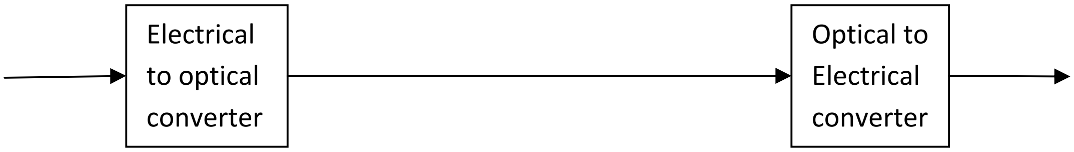
Optical fiber is established as the medium of choice for high-capacity long haul digital transmission systems and is moving rapidly into the access area. Its use in high-speed local area networks is also widespread [3]. Many papers advocating MoF for high data rate transmission in the research literature have been qualitative. Various approaches have been suggested for enhancing the higher bit rate but till now experiments are limited to low bit rate data transmission. All the papers are related to single tone data transmission. But in many applications we want to use multi tone system so that we can transmit data in various formats. In this paper, we present single tone and multi tone MoF system for high data transmission rates based upon direct detection method.

This thesis is divided into six modules. In the first module, the brief introduction about the Microwave over fiber communication system is presented. In second module a descriptive model is proposed for single tone and multi tone MoF system. The intensity modulation direct detection technique is used for converting microwave signal to base band signal which is used in fibers. In the third module, the description of the simulation setup for single tone MoF is given. The simulation setup for multi tone MoF is described in fourth module. The simulation results for both systems have been discussed in the fifth module. The sixth module gives the conclusion.

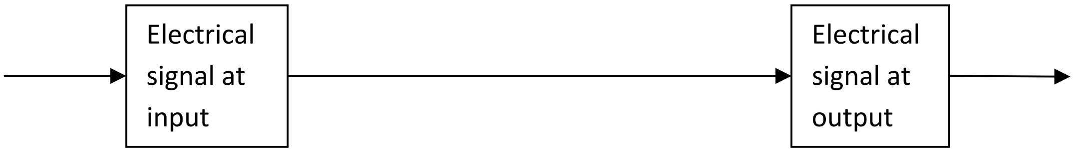
3.2 DESCRIPTIVE MODEL

Microwave over fiber technologies are of great interest for many potential applications such as broad-band wireless access networks, sensor networks, radar and satellite communication systems, and have been extensively studied in the last few years. The key function of a microwave-over-fiber network is to distribute microwave and millimeter-wave signals over optical fiber to take the advantages of the low loss, low dispersion, and large bandwidth of optical fiber links. On the other hand, it is also highly desired that the distributed signals can be processed directly in the fiber link without optical–electrical (O/E) and electrical–optical (E/O) conversions [60].

An optical transmission link with its equivalent in conventional microwave technology is shown in figure 3.1 For the transmission of microwave signal over fiber, the input electrical signal requires to be converted into optical form at the input to the fiber and to be returned to the microwave domain at the output. The extra components required for this purpose have to be weighed against the advantages of the fiber transmission medium [4].



(a) Optical transmission medium



(b) Electrical transmission medium

Figure 3.1 Optical and electrical transmission links for microwave signals

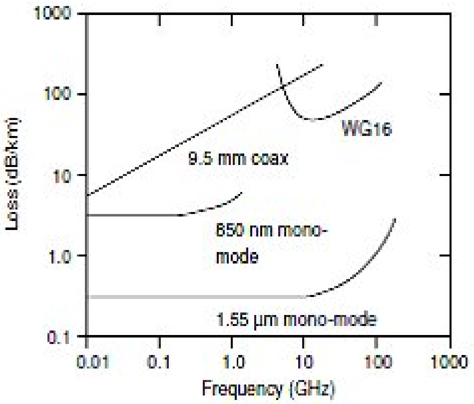


Figure 3.2 Losses of various transmission media as a function of signal frequency

The most obvious advantage of fiber transmission is to reduce losses relative to metallic media. A comparison between different losses in silica fiber at wavelengths of 850nm and 1550 nm are shown in figure 3.2. It shows that fiber has lower losses at microwave signal frequencies [4]; the rise in effective loss at the higher microwave frequencies is due to dispersion power penalties [61]. For a 1 dB penalty, the fiber bandwidth can be approximated by the equation

where $\Delta\lambda$ is the source line-width, D is the fiber dispersion, and L the fiber length. For microwave transmission purposes, the preferred wavelengths are either 1550 nm, using dispersion-shifted or dispersion-flattened fiber, or 1300 nm, using standard fiber and accepting the ~0.2 dB/km loss penalty [5].

The basic approach to optical signal modulation and recovery is based upon intensity modulation direct detection technique (IMDD). A schematic diagram of IMDD is shown in figure 3.3. The optical source intensity is directly modulated by the input microwave signal. An analog input is also applied to this intensity modulator. This modulator covert the electrical signal into optical form so that it can be compatible with fiber. The resulting intensity-modulated signal passes through the optical fiber to the photodiode where the modulation is returned to the electrical domain.

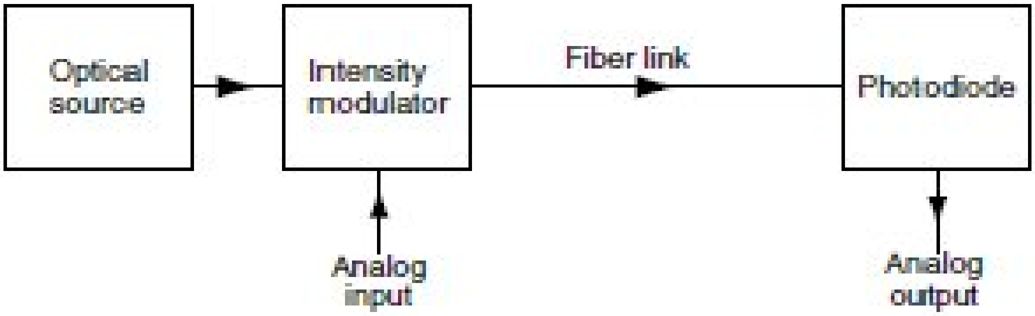


Figure 3.3 IMDD transmission system

Fiber Laser: The use of optically pumped fiber doped with an appropriate lasing ion has made a key contribution to optical communication through the optical fiber amplifier. The required doped fiber length depends on cavity losses, pump power, and lasing ion doping concentration. The latter is limited by clustering, so that practical erbium-doped fiber lasers for operation at 1530 nm wavelength typically require doped fiber lengths of 1-5 m, giving laser mode separations of 100-20MHz [14].

Semiconductor lasers: These are mostly used as sources in all optical communication systems. In IMDD, these sources provide direct electrical pumping and modulation. The simplicity of direct modulation of semiconductor lasers has proved attractive for many applications, and following early work on modulation characteristics, rapid progress has been made in reducing electrical parasitic of laser structures and optimizing laser parameters for high-speed operation [17]. The introduction of multiple-quantum-well (MQW) active regions led to considerable reductions in threshold current and an increase in differential gain by up to a factor of 2 relative to bulk devices [18]. Multi-section distributed feedback (DFB) lasers have been realized with tuning ranges of 10 nm, while maintaining linewidths less than 20 MHz [19]. Wider tuning ranges have been achieved in vertically coupled structures [20].

Optical Amplifiers: Gain, the optical amplifier parameter, need to be greater than unity. So, different developments are done to realize the amplifiers having gain greater than unity. They can also be used to compensate for splitting losses in multipoint distribution systems. The most important optical amplifier technologies for microwave signal transmission applications are the traveling wave semiconductor laser amplifier (SLA) [19] and the doped fiber amplifier (DFA) [24]. When the modulation frequency is greater than the reciprocal of the carrier lifetime, typically 2 ns, the distortion is seen to be small. This restricts the minimum intensity modulation frequency to several GHz, making them unsuitable for a number of wireless system applications, such as cellular radio signal distribution. The DFA is pumped using a semiconductor laser and has the advantage that it can be spliced directly into a fiber system, avoiding significant coupling losses. Since the fluorescence lifetime of erbium is long (>10 ms), low distortion performance can be maintained for modulation frequencies down to the GHz region [25].

Photodetectors: For microwave signal transmission, depletion layer photodetectors are preferred for their speed and good quantum efficiency. For such devices, 3 dB bandwidths in excess of 100 GHz were demonstrated some years ago [26]. In high dynamic range microwave photonic systems, detector power handling and nonlinear effects are of great importance. The effect of the generated carriers on the electric field within the detector is an important limiting factor [27-28].

3.3 SIMULATION SETUP FOR SINGLE TONE

The simulation setup for single tone microwave over fiber communication system is shown in figure 3.4. In this setup 4 users are transmitting their data through a single fiber. This project simulated in OPT Sim 4.7.1 specified in sample mode which carries different components to generate the required circuit and gives the finally result. Various parameters are set so that desired results can be achieved.

This set-up uses a different combination of optical preamplifiers (EDFA or SOA) with direct laser modulation. This system analysis requires the estimation of the electric- optical- electric frequency response in terms of harmonic generation. A single tone modulates a laser output using a direct laser at 1550 nm. The modulation frequency is varied from 1 to 20 GHz through parametric run. Propagation is modeled with an amplifier since the system is employed over long distance. At the receiver section, the two channels are splitted, amplified (with an EDFA or SOA) and detected.

Sinusoidal wave generator is used to generate a signal of 1 GHz frequency. This signal is fed to four different combiners where another signal coming from the bias wave generator is also combined. Four different electrical combiners are used to combine these signals. Four electrical filters are applied to achieve a 3 db gain to different signals coming from combiners. These electrical signals are modulated and converted into optical signal by using rate equation lasers. The center emission wavelengths of all different lasers are set to different wavelength in a range of 1549.5nm to 1550.5 nm.

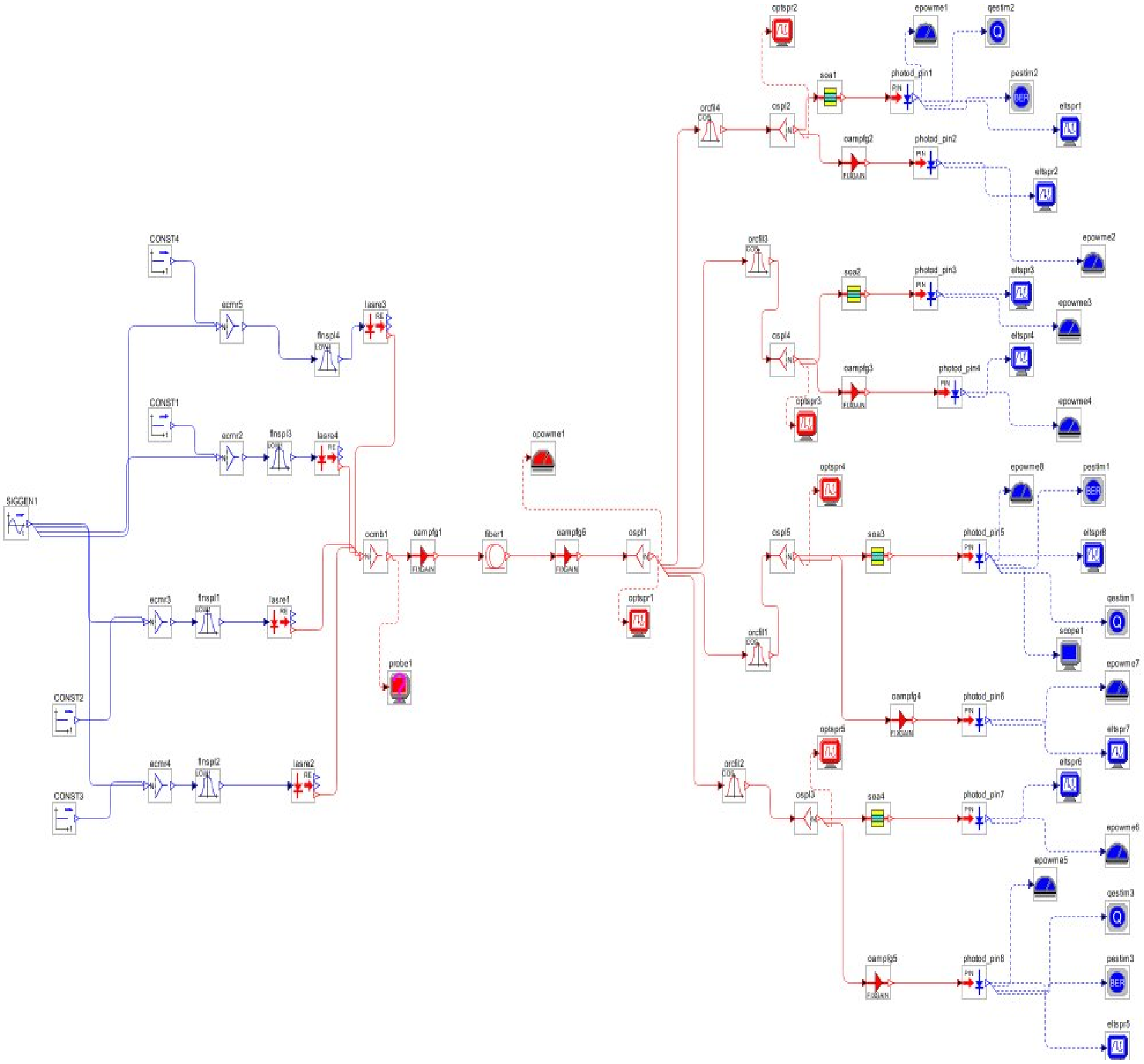


Figure 3.4 Simulation setup for single tone microwave over fiber communication system using 4 users

These signals are combined with the help of an optical combiner. Then fixed gain optical amplifier is used with 16 dB gain to amplify the signal and then this signal is passed through an optical fiber having a 100 Km distance. At the receiver side, this signal is again amplified through fixed gain optical amplifier and then this signal is splitted into four signals. Each signal is detected in two ways: first by using EDFA and second by SOA.

To monitor the detected signals electrical spectrum analyzer, electric power meter, electrical scope, Q estimator and BER estimator have been placed. The power meters measure the power at the frequency of the modulating tone and its double. Various eye diagrams at different frequencies are taken. The Q, jitter and BER values are also calculated to verify the results.

3.4 SIMULATION SETUP FOR MULTI TONE

The system characteristics are the same as the previous single tone setup. In this case, however, two modulating tones are employed. The frequency of one tone is varied from 1 to 20 GHz through parametric runs, while the other one is fixed at 5 GHz. The simulation setup for multi tone microwave over fiber communication system is shown in figure 3.5.

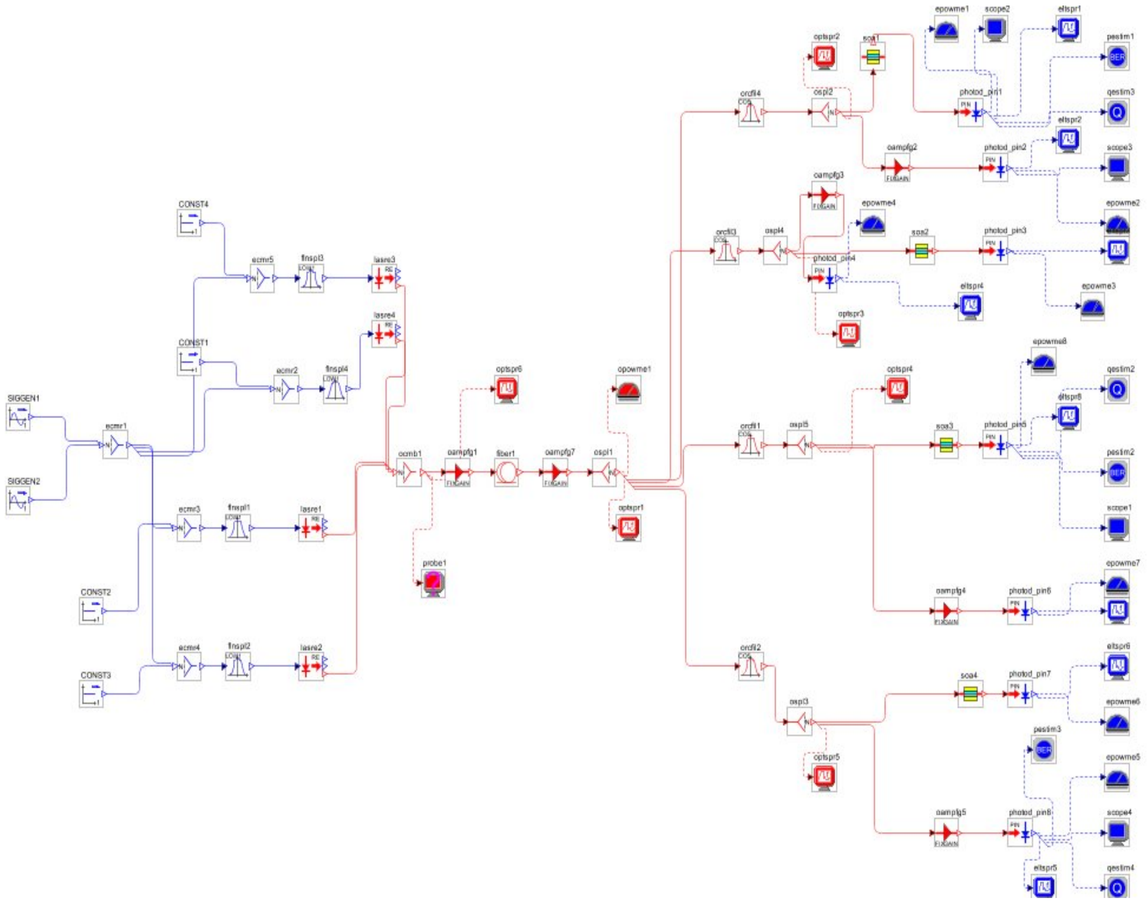


Figure 3.5 Simulation setup for multi tone microwave over fiber communication system using 4 users

In this setup 4 users are transmitting their data through a single fiber. This project is also simulated in OPT Sim 4.7.1 specified in sample mode. The data in various formats can be transmitted using multi tone. Two sinusoidal wave generators are used to generate the 1 GHz and 15 GHz signals. These signals are combined with the help of electrical combiner. Then this signal is fed to four different combiners where another signal coming from the bias wave generator is also combined as in case of single tone MoF system. All other system characteristics are the same as single tone microwave over fiber communication system.

The fixed gain optical amplifier is used with 30 dB gain to amplify the signal passed through an optical fiber having a 25 Km distance. Different measuring meters are applied at the receiver side to verify the results.

3.5 RESULT AND DISCUSSION

In this system, four users are of different step signals are combined with carrier radio frequency and transmitted over the fiber transmission, so simulation is done for different frequencies for different users and different waveforms will be observed. BER and eye diagram by varying frequency is calculated and other spectrums are observed and further in future users are capable of using high frequencies.

The figure 3.6 shows the eye diagrams of single tone microwave over fiber communication system using 4 users at different frequencies. It can be analyzed that the eye opening at 5 GHz is more than other frequencies. Maximum noise is present at 1, 4, 10, 15 and 20 GHz frequency and also there is noticeable noise at other frequency except 5 GHz. So the users can use 5 GHz frequency spectrum to send their data. The properties of all other component like Bessel filter, EDFA, wave generator are designed to operate at 5 GHz region. Hence, at 5 GHz frequency gives the best performance to operate single tone microwave over fiber communication system.

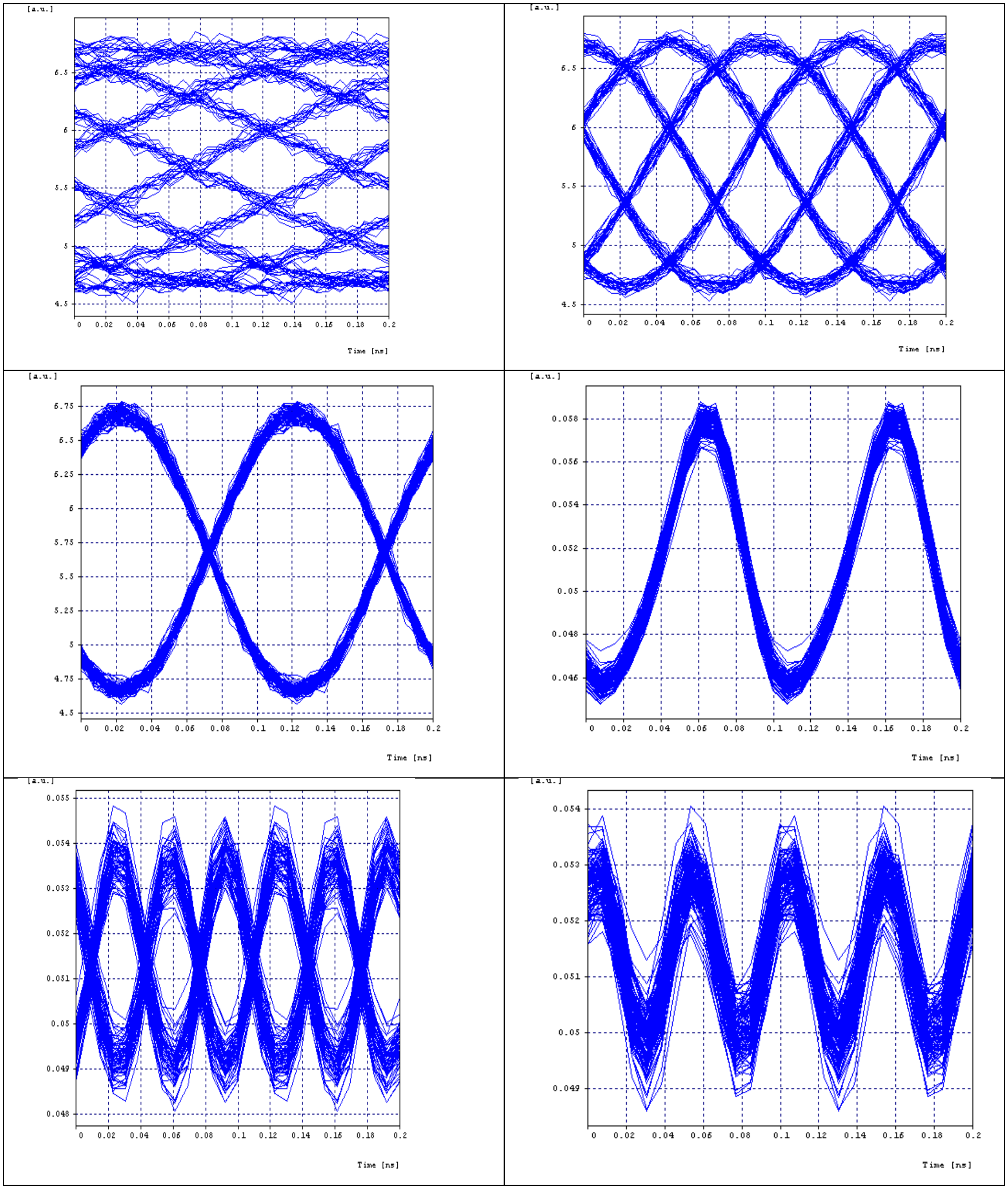


Figure 3.6 Eye diagram of single tone microwave over fiber communication system using 4 users at 1, 4, 5, 10, 15, and 20 GHz frequencies

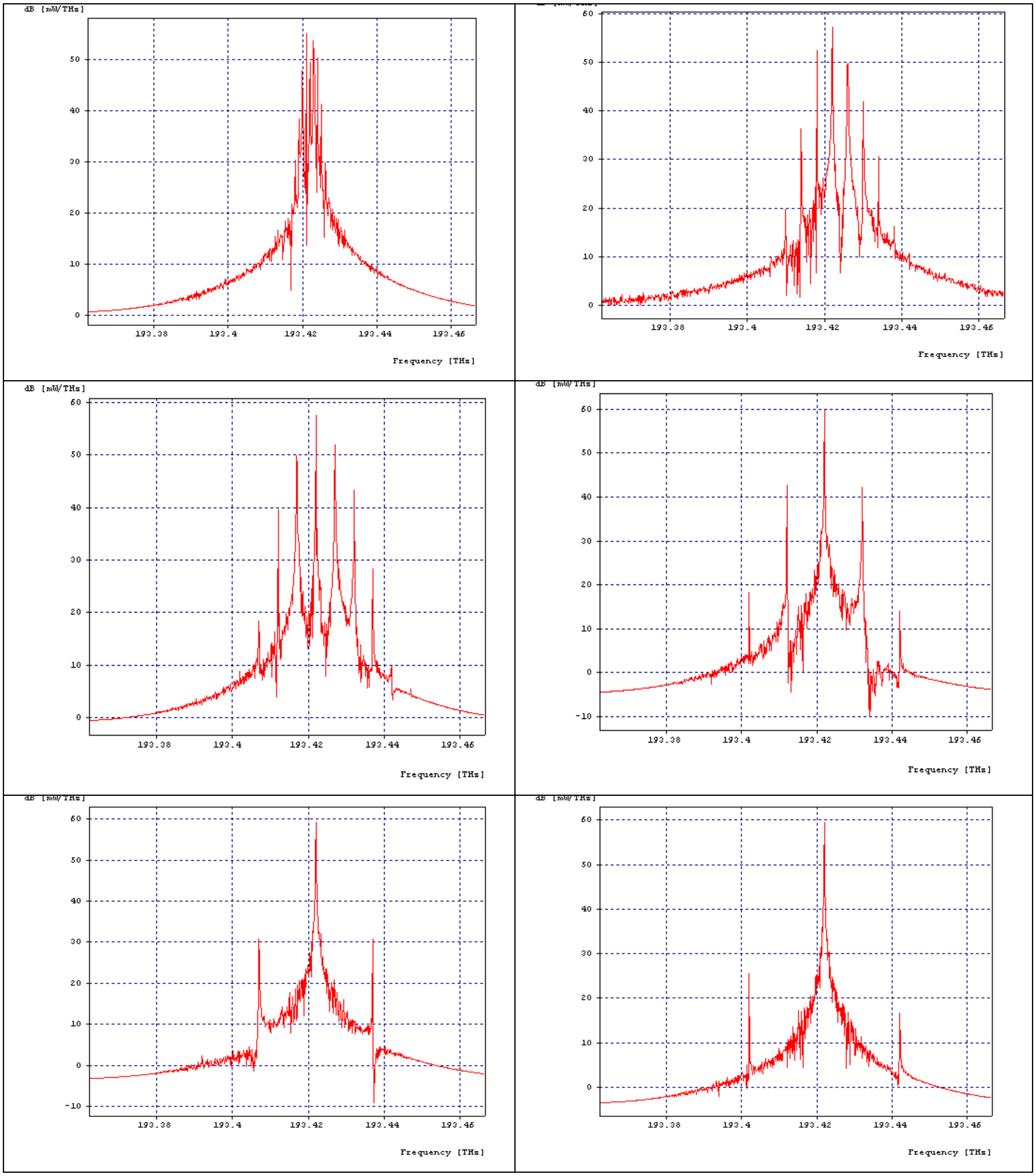
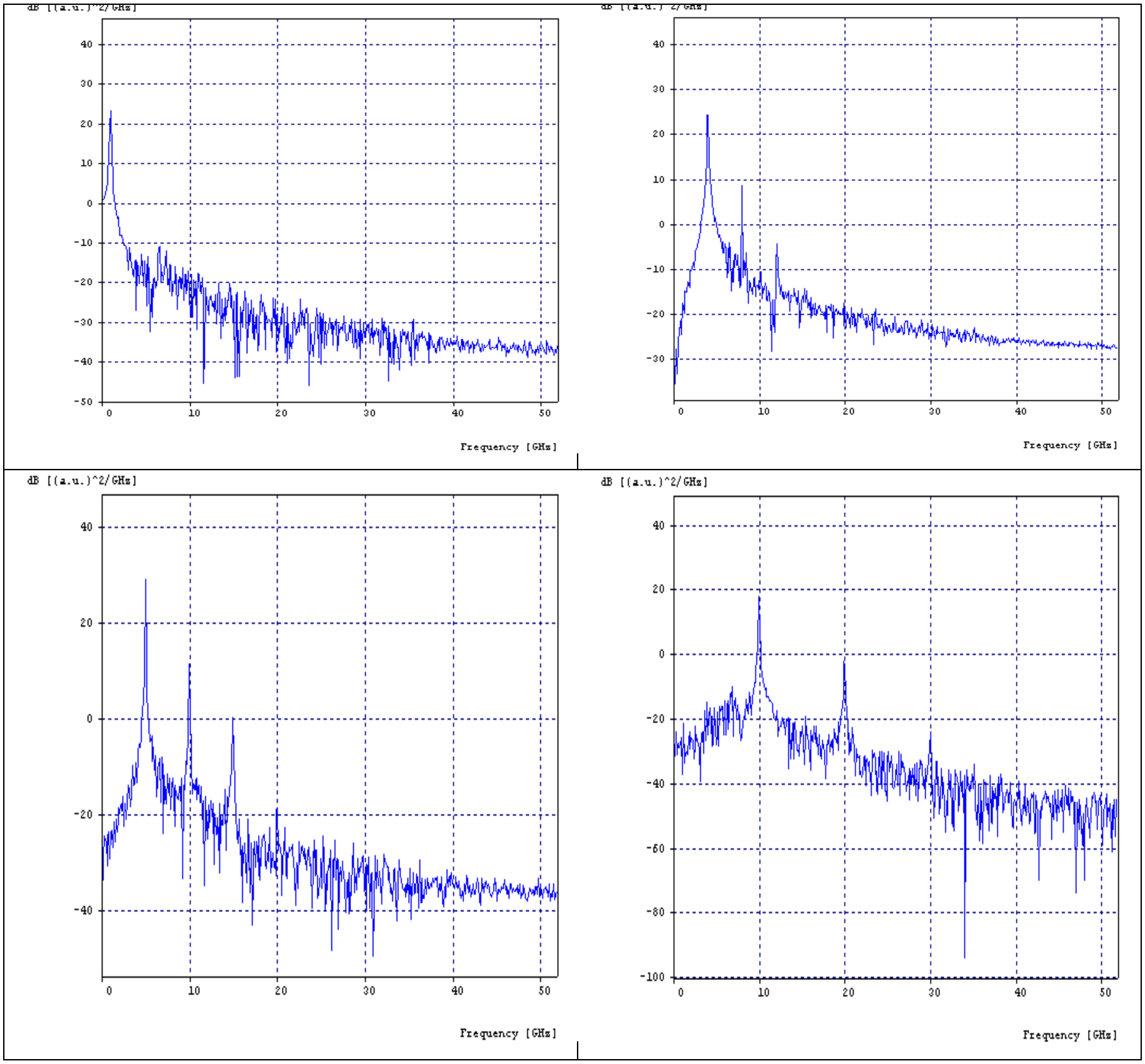


Figure 3.7 Optical spectrum of single tone microwave over fiber communication system using 4 users at 1, 4, 5, 10, 15, and 20 GHz frequencies

The figure 3.7 shows the optical spectrum of single tone microwave over fiber communication system using 4 users at different frequencies. As shown in eye diagram, the distortion increases as the frequency increase. So we have very less distorted diagram at 5 GHz as compare to distorted optical spectrum at 20 GHz.



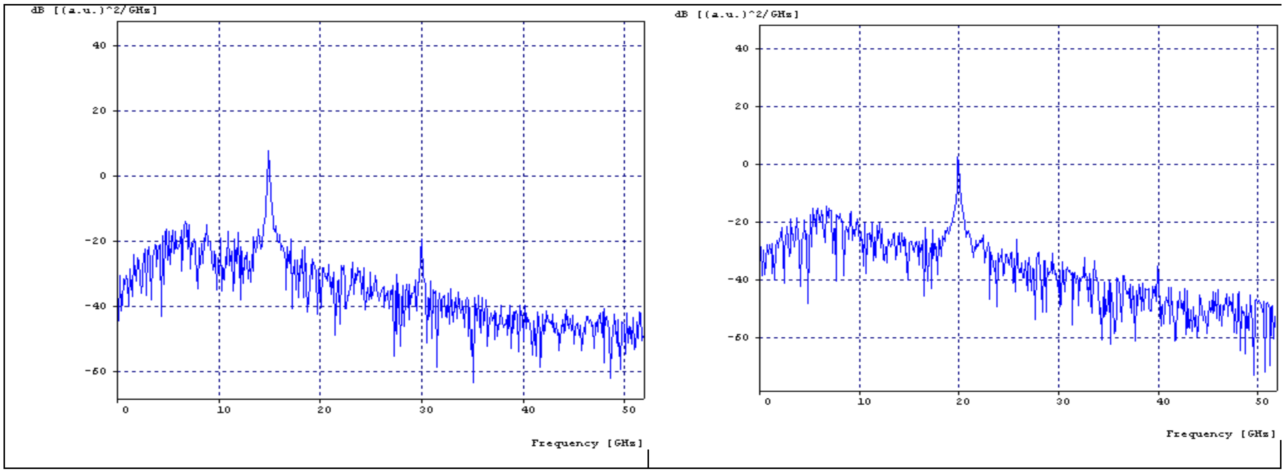


Figure 3.8 Electrical spectrum of single tone microwave over fiber communication system using 4 users at 1, 4, 5, 10, 15, and 20 GHz frequencies

The above figure 3.8 shows the electrical spectrum of single tone microwave over fiber communication system using 4 users at different frequencies. It can be analyzed that distortion increases as the frequency increase, which is also shown in eye diagrams and optical spectrum. So we have very less distorted diagram at 5 GHz as compare to distorted optical spectrum at 20 GHz.

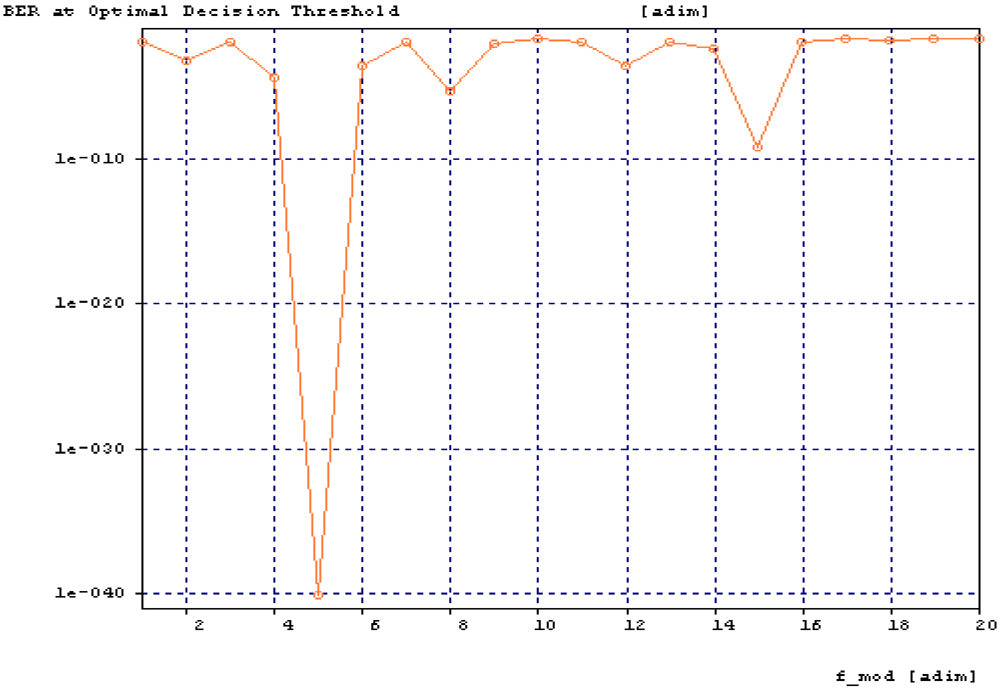


Figure 3.9 BER diagram for single tone microwave over fiber communication system using 4 users at 1 to 20 GHz frequency range

Figure 3.9 shows BER diagram for single tone microwave over fiber communication system using 4 users at 1 to 20 GHz frequency range. It is analyzed that there is negligible BER at 5 GHz frequency. But at other frequencies, the effect can be noted. At 5 GHz the BER is achieved upto 1e-40 i.e. 10 . So, this BER shows we can transmit data efficiently. It can be seen that the minimum BER is achieved at 4 to 5 GHz frequency range. Hence with increase in frequency, the value of BER is increased.

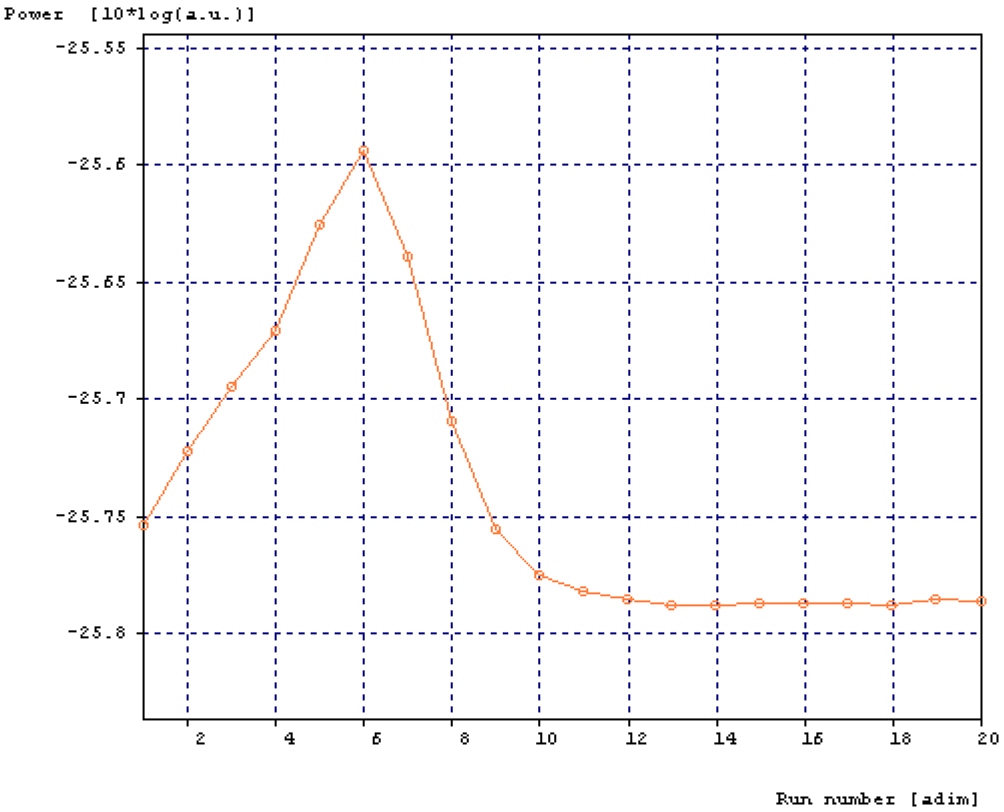


Figure 3.10 The correlation diagram of power Vs frequency for single tone microwave over fiber communication system using 4 users at 1 to 20 GHz frequency range

Figure 3.10 shows a correlation diagram of power Vs frequency for single tone microwave over fiber communication system using 4 users. A frequency range from 1 GHz to 20 GHz is taken in this diagram. It is analyzed that the maximum power is achieved at 5 GHz frequency. But at other frequencies, the power is less. If we increased the frequency above 10 GHz, then the power level is very low and is not sufficient to transmit the data and with increase in frequency, the value of power level is decreased. So, the 5 GHz frequency is best suitable for transmitting data in single tone microwave over fiber communication system.

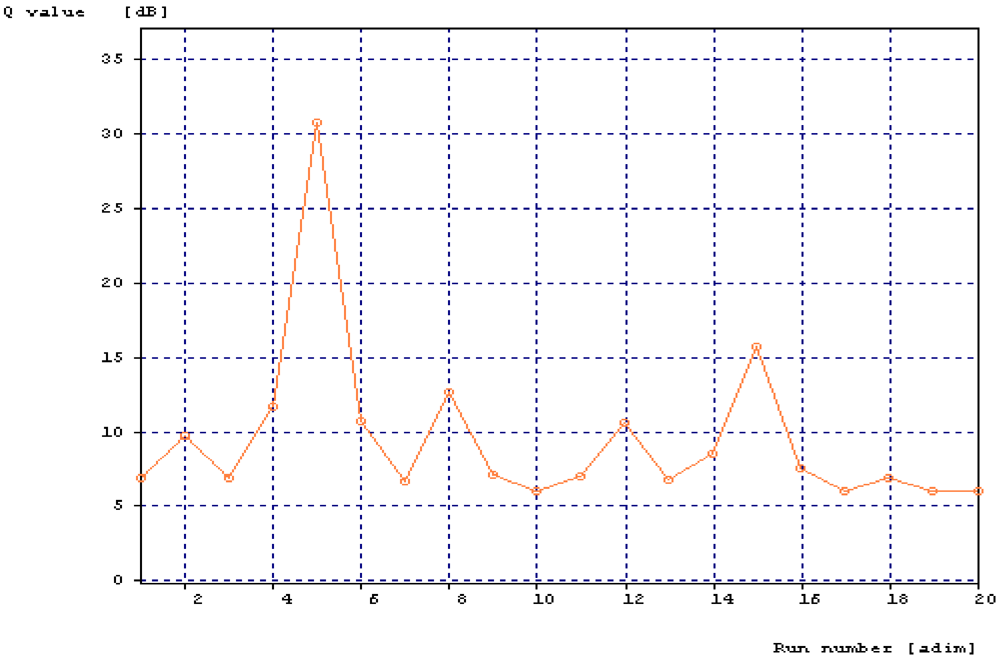
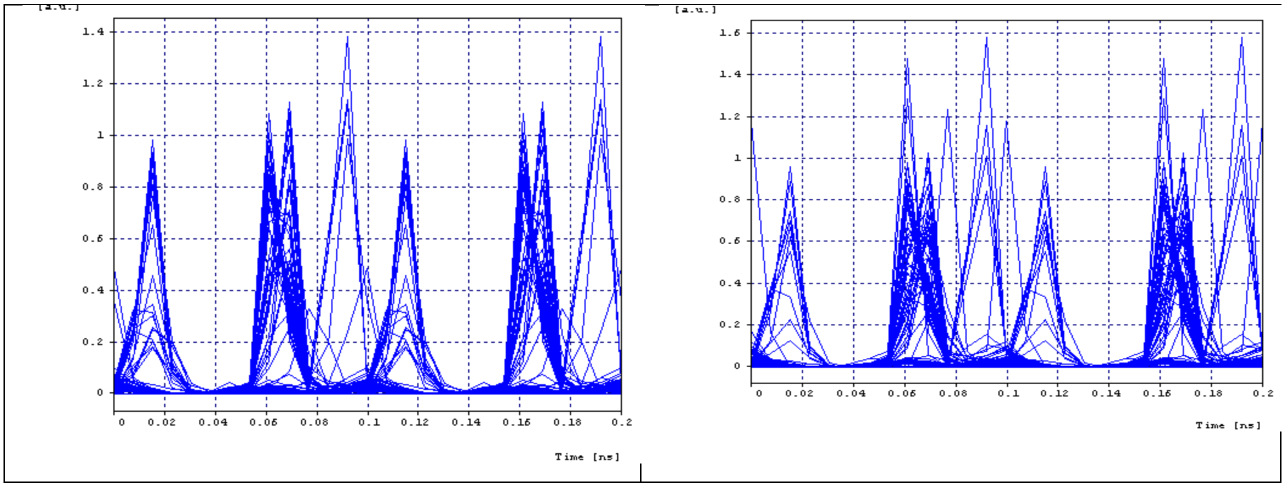


Figure 3.11 The correlation diagram of Q parameter Vs frequency for single tone microwave over fiber communication system using 4 users at 1 to 20 GHz frequency range

Figure 3.11 shows a correlation diagram of Q parameter Vs frequency for single tone microwave over fiber communication system using 4 users. A frequency range from 1 GHz to 20 GHz is taken in this diagram. It is analyzed that the maximum value of Q is achieved at 5 GHz frequency. But at other frequencies, the value is less. It can be seen that the maximum Q is achieved at 4 to 5 GHz frequency range. Hence with increase in frequency, the value of Q is decreased. So, the 5 GHz frequency range is the best suitable for transmitting the data.



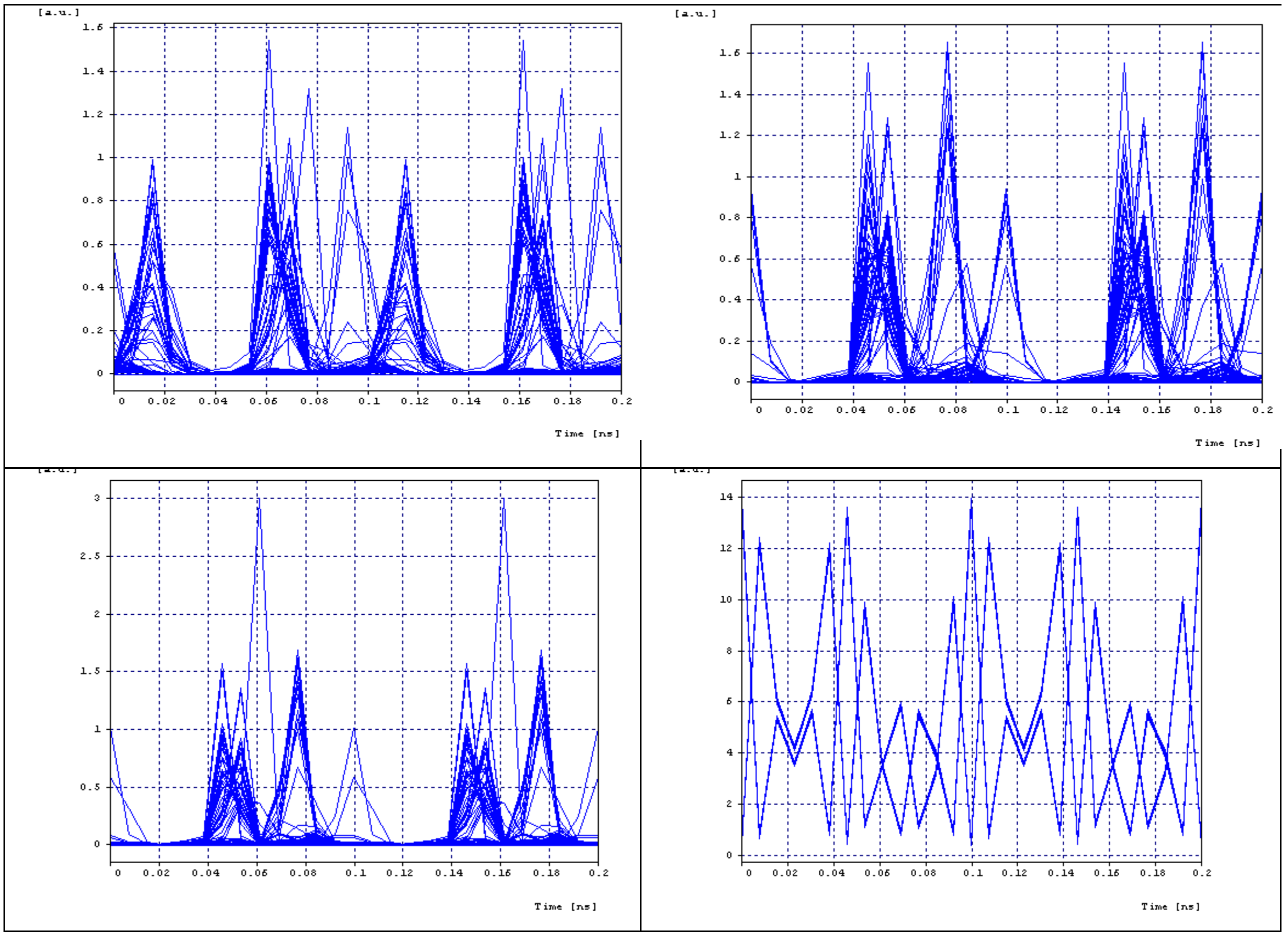


Figure 3.12 Eye diagram of multi tone microwave over fiber
communication system using 4 users at 1, 4, 5, 10, 15, and 20 GHz frequencies

The above figure 3.12 shows the eye diagrams of multi tone microwave over fiber communication system using 4 users at different frequencies. It can be analyzed that the noise at 5 and 15 GHz frequencies is less than other frequencies. Maximum noise is present at 1, 4, 10 and 20 GHz frequency and also there is noticeable noise at other frequency except 5 GHz. So the users can use 5 and 15 GHz frequency spectrum to send their various types of data e.g. for audio signal 5GHz frequency ban can be used whereas 15 GHz can be used to transmit video signal. The properties of all other component like Bessel filter, EDFA, wave generator are designed to operate at 5 and 15 GHz region. Hence, at 5 and 15 GHz frequency gives the best performance to operate multi tone microwave over fiber communication system.

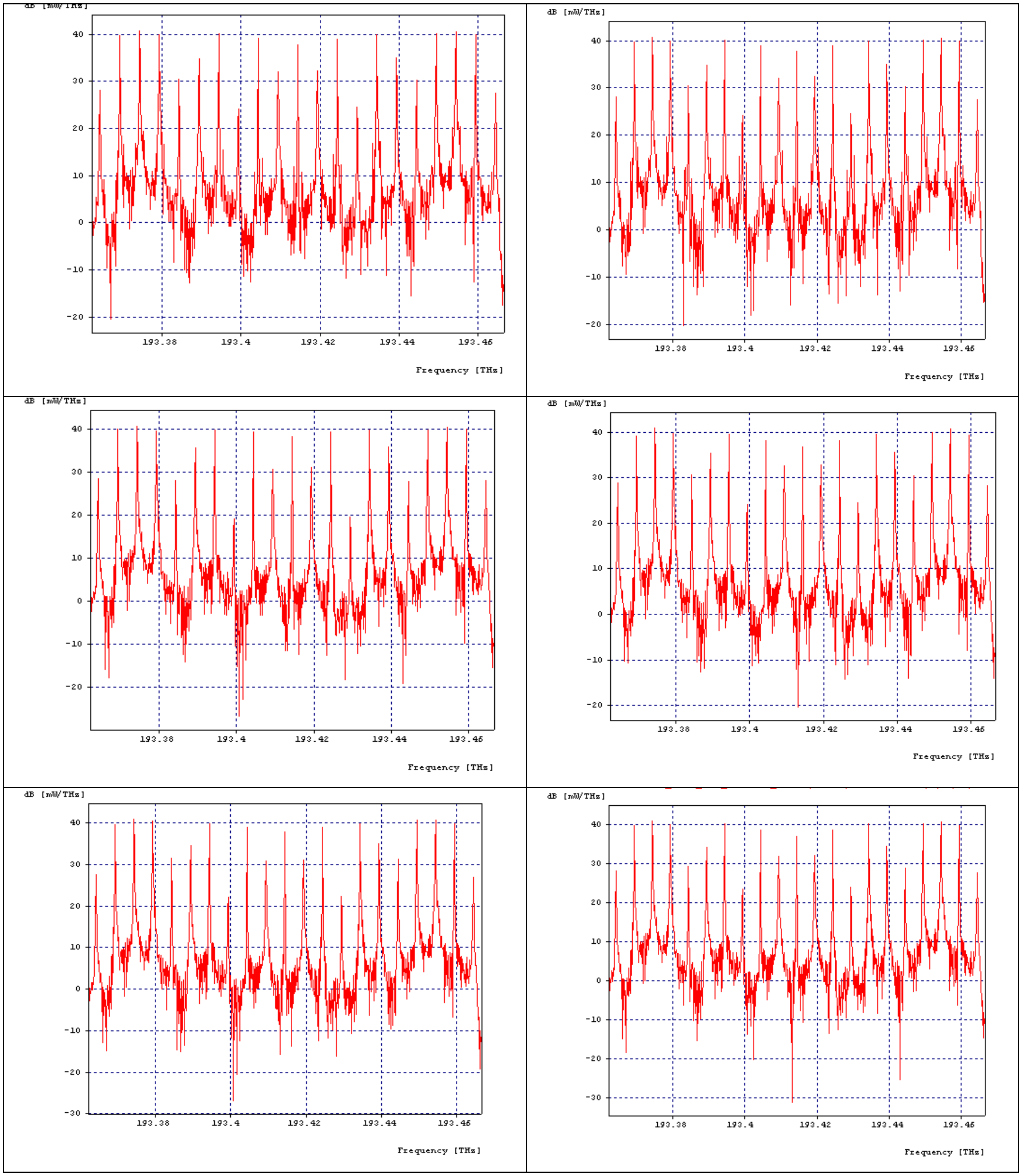
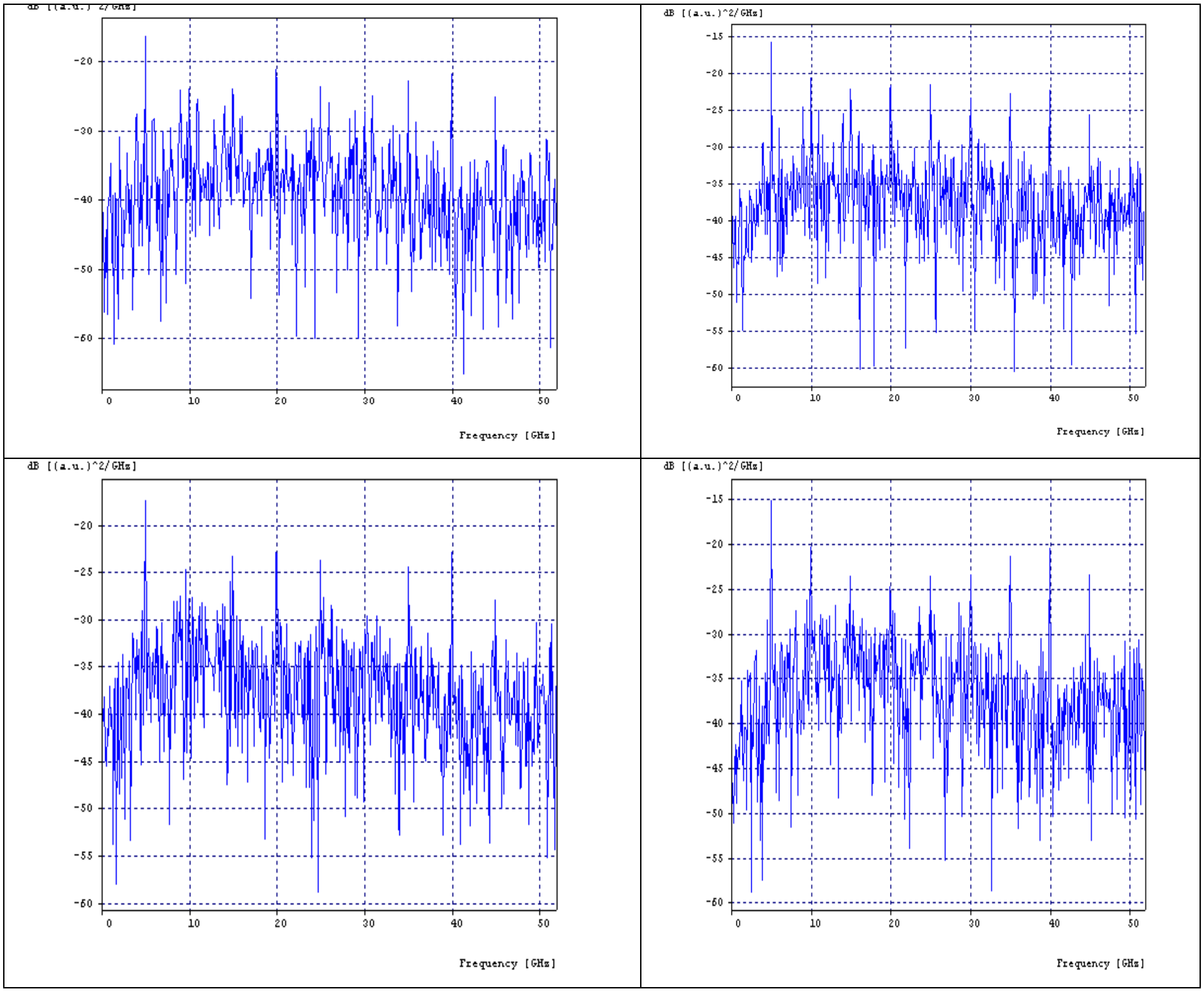


Figure 3.13 Optical spectrum of multi tone microwave over fiber communication system using 4 users at 1, 4, 5, 10, 15, and 20 GHz frequencies

The above figure 3.13 shows the optical spectrum of multi tone microwave over fiber communication system using 4 users at different frequencies. As shown in eye diagram, the varying distortion is noticed at the different frequency. So we have very less distorted diagram at 5 GHz and 15 GHz region as compare to distorted optical spectrum at other frequencies.



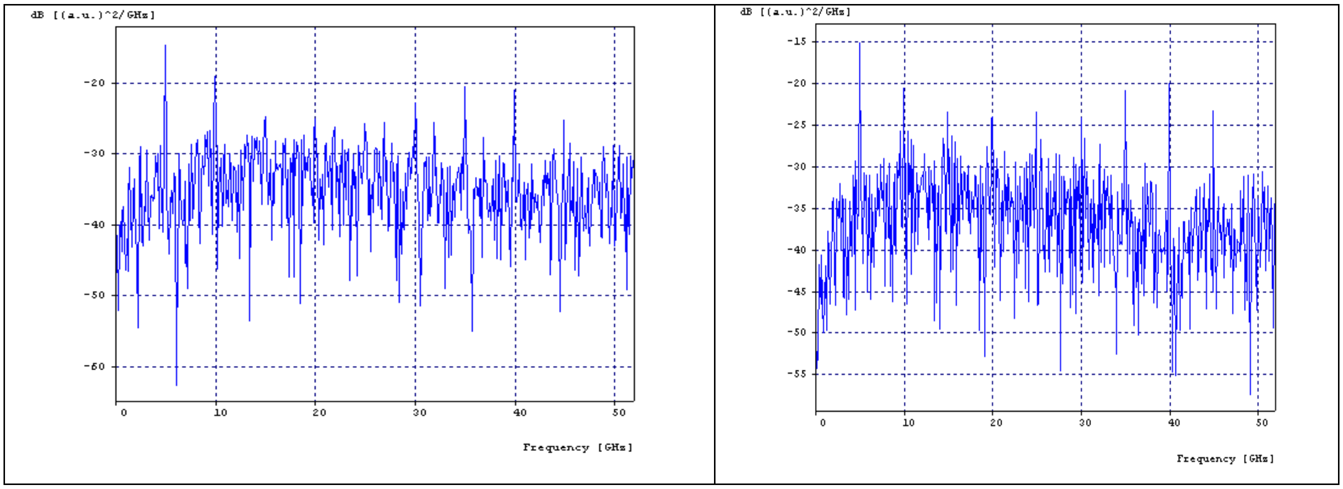


Figure 3.14 Electrical spectrum of multi tone microwave over fiber communication system using 4 users at 1, 4, 5, 10, 15, and 20 GHz frequencies

The above figure 3.14 shows the electrical spectrum of multi tone microwave over fiber communication system using 4 users at different frequencies. It can be analyzed that distortion differs at the various frequency bands, which is also shown in eye diagrams and optical spectrum. So we have very less distorted diagram at 5 and 15 GHz as compare to distorted optical spectrum at other frequencies.

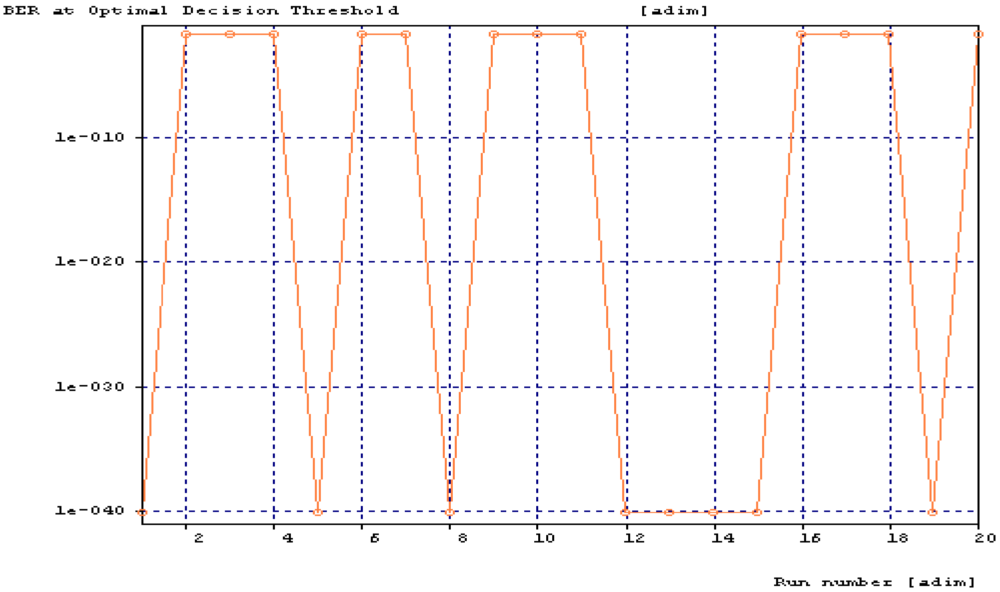


Figure 3.15 BER Vs frequency diagram of multi tone microwave over fiber communication system using 4 users at 1, 4, 5, 10, 15, and 20 GHz frequencies

Figure 3.15 shows BER diagram for multi tone microwave over fiber communication system using 4 users at 1 to 20 GHz frequency range. It is analyzed that there is negligible BER at near 5 and 15 GHz frequency band. Hence for transmission of different data we can use these two bands.

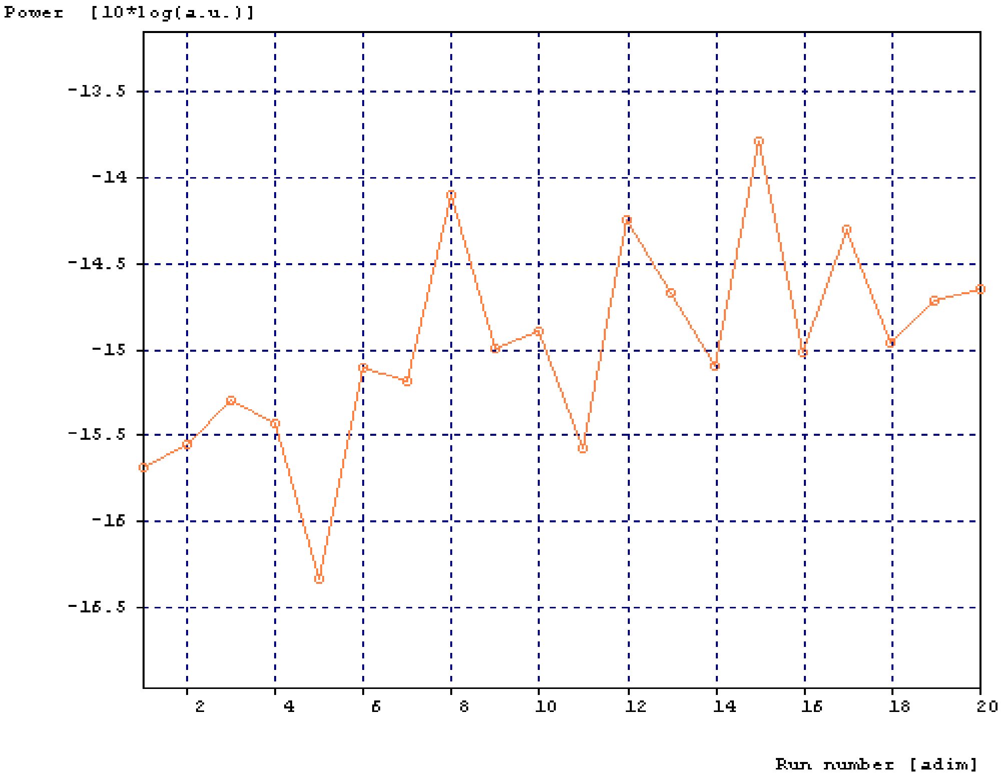


Figure 3.16 The correlation diagram of power Vs frequency for multi tone microwave over fiber communication system using 4 users at 1 to 20 GHz frequency range

Figure 3.16 shows a correlation diagram of power Vs frequency for multi tone microwave over fiber communication system using 4 users. A frequency range from 1 GHz to 20 GHz is taken in this diagram. It is analyzed that the maximum power is achieved at two frequency ranges i.e. 5 to 8 and 14 to 15 GHz frequency band. But at other frequencies, the power is less. So, these two frequency bands are best suitable for transmitting data in single tone microwave over fiber communication system.

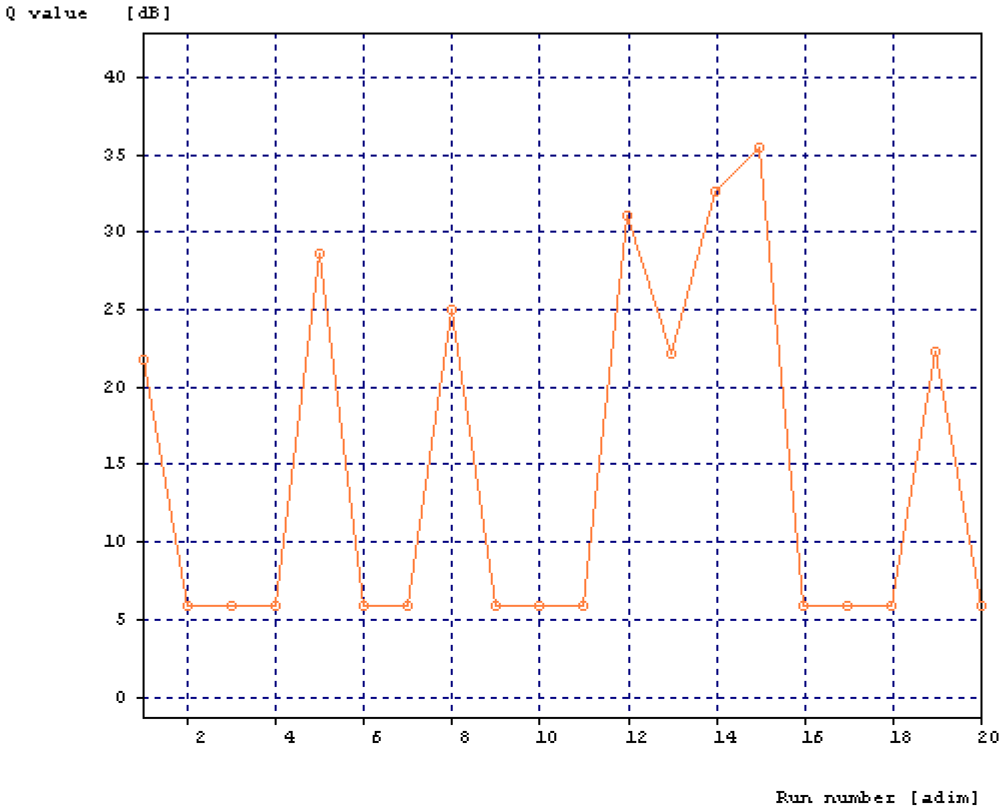


Figure 3.17 The correlation diagram of Q parameter Vs frequency for multi tone microwave over fiber communication system using 4 users at 1 to 20 GHz frequency range

Figure 3.17 shows a correlation diagram of Q parameter Vs frequency for multi tone microwave over fiber communication system using 4 users. A frequency range from 1 GHz to 20 GHz is taken in this diagram. It is analyzed that the effective q is achieved at two frequency ranges i.e. 5 to 8 and 14 to 15 GHz frequency band. But at other frequencies, the value is less. So, these two frequency bands are best suitable for transmitting data in single tone microwave over fiber communication system.

3.6 CONCLUSION & FUTURE SCOPE

The systems for the optical transmission of microwave signals have been analyzed and technologies for their implementation reviewed. IMDD systems offer the advantage of simplicity. However, large received optical power is necessary in order to overcome receiver thermal noise. In systems of length more than a few kilometres, the maximum source power is limited by the onset of nonlinear effects, especially SBS, in the optical fiber. In short systems, the limit is set by source and detector power handling limits. Optical pre-amplifiers enable near shot-noise-limited detection to be achieved even for low received powers. In particular, the availability of high-quality optical fiber amplifiers for the 1550 nm optical fiber transmission window makes it possible to realize high-quality IMDD transmission systems at that wavelength. The key function of a microwave-over-fiber network is to distribute microwave and millimeter-wave signals over optical fiber to take the advantages of the low loss, low dispersion, and large bandwidth of optical fiber links. In this paper, a microwave over fiber communication system using intensity modulation direct detection technique is reported. It has been concluded that two systems, single tone and multi tone can be recommended. From the eye diagrams, bit error rate (BER) and the Q-factor characteristics, it is clear that the single tone microwave system gives best performance at 5 GHz frequency for single tone system. By using multi tone various types of data can be transmitted at 5 GHz and 15 GHz frequency band. It is also analyzed that the output taken from EDFA is better than SOA. This is because EDFA amplifies all the frequencies simultaneously.

There is much scope for further work to improve component performance, particularly source output power, RIN, and modulation sensitivity; modulator insertion loss, power handling, and photo-detector power handling. The various parameters of microwave over fiber communication system using direct detection method can be modified using coherent system. The shot-noise limited receiver sensitivity is a major problem in detection of optical signal at receiver in direct detection. The direct detection systems are limited to intensity modulation (the use of angle modulation with interferometric detection at the receiver results in an intensity-modulated signal at the photodiode that has then to be detected conventionally and therefore does not yield SNR improvements) but there can be more types in modulation like frequency or phase modulation.

CHAPTER 4

HIGH DYNAMIC RANGE MICROWAVE PHOTONIC SYSTEM USING COHERENT SYSTEM

In this chapter, microwave over fiber using coherent system is demonstrated. A Mach–Zehnder modulator (MZM) is used to generate millimeter-wave using optical frequency and signal modulation. In this technique, at the base station (BS), the optical carrier can be reused to carry upstream data and delivered to the central station (CS). Different results show that coherent system has better quality and is almost robust to fiber chromatic dispersion. Lorentzian laser is used with MZM to achieve a conversion of microwave band into baseband at which fiber operates. The key device in the coherent system is a Mach-Zehnder modulator which performs all-optical microwave mixing with semiconductor laser. The single pole low pass filter is realized by passing the microwave signals, acting as a dispersive device. An optically converted signal is obtained at the end of laser and this signal passes through a single mode fiber**.** This system can also use for two modulating tones. In multi tone system, the frequency of the first tone is varied from 1 to 20 GHz and second is set at 5 GHz. A data signal of 18 Gbps is transmitted over long haul single mode fiber by single tone system. A very good bit error rate (BER) 10 performances in a 100 Km and 50 Km fiber link is achieved for both single tone and two tones respectively in proposed microwave over fiber communication system.

4.1 INTRODUCTION

Microwave-over-fiber (MoF) has attracted much attention as a convenient way of distributing microwave signals. An optical fiber system uses light to carry a microwave subcarrier on optical fibers. The microwave is usually frequency modulated for wireless broadcasting [4]. To realize low cost and high transmission performance in MoF, coherent systems are the best suitable method. Due to rapidly use for transmission and distribution of wireless signals, this techniques have become very attractive in realizing future broadband wireless networks. Optical millimeter-wave signal generation and simple configuration of base station are the main advantage of this system [3]. To realize optical millimeter-wave generation by frequency up-conversion, many techniques have been reported, such as frequency quadrupling using optical frequency multiplication technique [62], cross-gain modulation in a semiconductor amplifier [35], the frequency up-conversions using four-wave mixing [31], frequency doubling using an optical carrier suppression modulation [29], optical heterodyne detection with optical interleaving [34] Because a low cost MZM can be used to generate optical millimeter-wave signal, it has been considered to be a cost-effective solution [47].

Fei zeng et al. [60] proposed and demonstrated an all-optical signal processor that performed both microwave mixing and band pass filtering in a radio-over-fiber link. The key device in the processor was an electro-optic phase modulator which performs all-optical microwave mixing. An up or down-converted microwave signal was obtained and other unwanted frequency components were rejected at the end of the fiber span. The use of the proposed signal processor to perform an up-conversion of a microwave signal from 3 to 11.8 GHz in a 25-km fiber link was demonstrated.

M. Garcia Larrode et al. [34] employed the OFM technique. The limitation of the modal bandwidth of an MMF link was overcome in ROF systems. In the experiment, OFM was applied to generate microwave carriers up to 40 GHz and distribute them over 4.4 km of MMF link. Also, 16-QAM and 64-QAM radio signals were up-converted from 300 MHz to 23.7 GHz and 29.7 GHz, and recovered successfully after the MMF link.

Hai-Han Lu et al. [43] proposed a full-duplex ROF transport system based on main and multiple side modes injection-locked DFB LD. The establishment of ROF systems with WIMAX data stream and achieved good BER performance over a 120 km SMF links for both down/uplinks was investigated. The experimental results showed that the proposed system was applicable for long-haul full-duplex microwave optical links. A data signal of 70 Mbps/10 GHz (WiMAX) signal was transmitted over long-haul single-mode fiber (SMF) transmission.

J. He et al. [47] demonstrated two schemes of full duplex Radio over fiber (ROF) systems with frequency-quadrupled optical millimeter-wave generation and wavelength reuse for uplink connection. In the two schemes, as a MZM driven by an RF at 10 GHz, 40 GHz millimeter-wave was generated, which reduced the bandwidth of microwave, component and modulator. A comparison of two schemes considering the impact of fiber chromatic dispersion was discussed. For scheme A, the millimeter-wave with frequency quadruple was generated only by one MZM. But in this system, the millimeter-wave power fluctuated due to constructive and destructive interaction between the two beatings induced by chromatic dispersion. For scheme B, only the generated millimeter-wave was modulated by downstream data, the optical carrier was not. So the upstream data carried by the optical carrier had better performance.

Du to easiness and more utilization of wireless network, there is a need to up-grade the wireless system. Many research literatures have been qualitative and suggested in this field. To achieve a high data rate transmission in wireless system, optical fiber can be used. The Recently, MoF Technology has been studied to enhance the wireless transmission. Various approaches have been suggested for enhancing the higher bit rate but till now experiments are limited to short distance and have a very low bit rate data transmission. Also, the research is related to single tone data transmission. But in many applications, there is a need for multi tone system so that data in different formats can be transmitted. In this chapter, we present single tone and multi tone MoF system for high data transmission rates with the help of coherent system. An intensity modulation direct detection technique is also used for this purpose but this technique has its limitation. When employing conventional optical intensity modulation direct detection (IMDD) system, in the micro / millimeter wave-over-fiber link, the signal quality is affected by the combined effect of received signal level fluctuation. Also, multipath fading and nonlinear intensity modulation degraded the microwave signal.

This chapter is divided into five modules. In the first module, the brief introduction about the Microwave over fiber communication system is presented. In second module a descriptive model is proposed for single tone and multi tone MoF system. The simulation setup for both systems is described in the third module. The simulation results have been discussed in the forth module. The fifth module gives the conclusion and future scope.

4.2 DESCRIPTIVE MODEL

The block diagram of a coherent system is shown in figure 4.1. In this system, the optical source is modulated in intensity, frequency, or phase by the input microwave signal, either directly or by passage through an external modulator. The modulated signal passes through the optical fiber to the receiver, where it is combined with the output from a local oscillator (LO) laser.

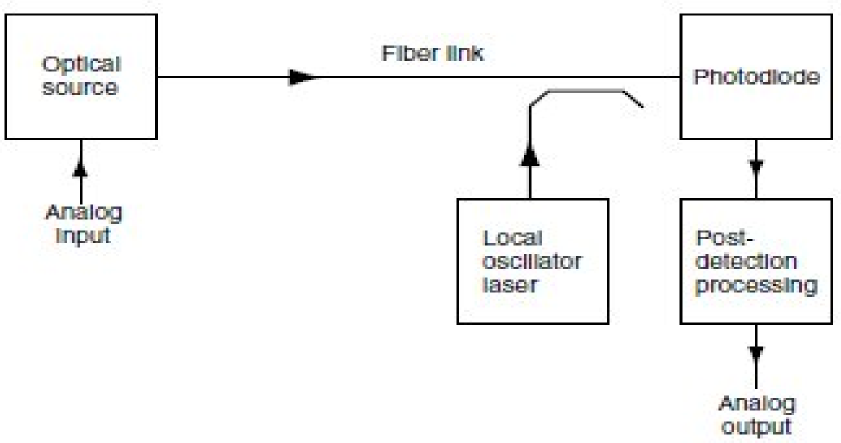


Figure 4.1 Coherent transmission system

The combined signal illuminates the photodiode to produce an electrical signal centered on the difference frequency between the unmodulated optical source and the LO laser. This signal is further processed to recover the analog output signal [4].

Heterodyne or homodyne detection is used to convert the optical signal to a baseband electrical signal in coherent receivers. The coherent receiver has the following advantages against direct detection:

(1) The shot-noise limited receiver sensitivity can be achieved with a sufficient local oscillator (LO) power. The LO gives us a signal gain, whereas the LO shot noise overwhelms the thermal noise of the receiver; thus by increasing the LO power, we can receive a signal with limited shot noise [13].

(2) The frequency resolution at the intermediate frequency (IF) or baseband stage is so high that we can separate closely spaced wavelength-division multiplexed (WDM) channels at the electrical stage.

(3) The ability of phase detection can improve the receiver sensitivity compared with the IMDD system. This is due to the fact that the distance between symbols, which are expressed as phasors on the complex plane, is extended by the use of the phase information [4].

In coherent systems we can use two types of receivers; Heterodyne and homodyne receivers. Both have their advantages and disadvantages. In heterodyne receiver, IF should be higher than the signal bit rate, but the maximum bit rate should be always less than the half of that the square-law detector can achieve. In contrast, the homodyne receiver is essentially a baseband receiver; however, the complexity in stable locking of the carrier phase drift has prevented its practical applications [63].

The fundamental concept behind coherent detection is to take the product of electric fields of the modulated signal light and the continuous-wave LO. The optical signal coming from the transmitter can be described by

$$E(t) = A(t) \exp (j\omega t)$$

Where A(t) is the complex amplitude and ω is the angular frequency. Similarly, the field of the LO can be described by

$$(\;)= \quad \exp(\qquad)$$

Where   is the complex amplitude and   is the angular frequency of the local oscillator. Balanced detection is usually introduced into the coherent receiver as a mean to suppress the DC component and maximize the signal photocurrent. The sources of noise in a coherent system are similar to those in a direct detection system i.e. thermal noise and shot noise current generated in the photodiode load, optical source relative intensity noise and noise generated by any optical amplifiers [4]. These noises give carrier-to-noise ratio (CNR) after photo detection of

$$\mathrm{CNR} = \frac{\;}{\;}$$

Where   is the source output power, g is the fiber path gain, R is the photodiode responsivity, e is the electronic charge and B is the bandwidth.

There are three main disadvantages of coherent transmission systems relative to those using direct detection:

(i) The frequencies of the LO laser and signal must be controlled to differ by the required IF, whereas in the direct detection system, it is only necessary that the source laser frequency be suitable for the photodiode used.

(ii) The line-widths of source and LO lasers must be suitable for the modulation mode used, whereas in direct detection systems, the required source line-width is mainly determined by the optical fiber dispersion penalty.

(iii) The polarization state of the LO and signal must be matched at the photodiode [4].

Advanced semiconductor lasers can offer line-widths in the GHz region coupled with wavelength-tuning ranges in excess of 10 nm [22] although the commercial availability of such lasers is currently limited. Homodyne systems require the LO frequency to be phase-locked to that of the received signal in an optical phase-lock loop (OPLL). Realizing such loops with other than narrow line-width lasers presents formidable challenges [64].

Polarization matching can be achieved by active polarization control of the LO signal for maximum detected signal output [65] or using polarization diversity reception [66]. Whilst the disadvantages of coherent transmission systems can all be overcome, the penalty is a significant increase in system complexity relative to direct detection systems.

Semiconductor lasers: For coherent analog optical transmission systems generally require tunability for source/LO laser wavelength matching and channel selection, uniform FM frequency response for optical FM and phase-locked applications, and narrow line-width for high SNR in angle-modulated systems. Careful design of semiconductor laser structures to minimize spatial hole burning effects has led to the realization of MQW DFB lasers having line-widths below 100 GHz [23], a value sufficiently small to permit high SNRs in angle modulated systems. In coherent systems, semiconductor lasers are used with external modulators. The advantage that external modulation offers the link designer is the ability to design the laser separately from the modulation bandwidth or link linearity, which are determined by the modulator design. Since improvements in link loss, noise figure, and compression dynamic range rely on high detector photocurrents to obtain shot noise- limited operation, research has focused on the design of high-power low noise lasers. Examples of high-power semiconductor lasers include DFB [67] as well as low-gain designs [68] where power outputs have exceeded 150 mW and are nearing 1 W. Reviewing the state of semiconductor laser research, it is clear that sources suitable for high-performance coherent microwave transmission systems are realizable and such lasers have the attraction of low-cost manufacture.

External modulators: An external modulator is desired in coherent systems to avoid transmission system gain limitation due to limited source modulation sensitivity which is a problem in direct detection. For a Mach−Zehnder interferometric modulator operated well within its bandwidth, the modulation response is uniform [32]. These modulators operate by converting the incident light into photocurrent in their absorbing state. Coupling losses between optical fiber and semiconductor waveguide modulators can be reduced by moving to non-waveguide reflective modulator designs in which the light is incident perpendicular to the junction plane, as in the asymmetric Fabry−Perot modulator (AFPM). In common with other electro-absorption modulators, these devices can also be used as detectors to create a duplex system [34].

Optical Amplifiers: The most important optical amplifier technologies for microwave signal transmission applications are the traveling wave semiconductor laser amplifier (SLA) [35] and the doped fiber amplifier (DFA) [24]. Figure 4.2 shows the structure of an erbium-doped fiber amplifier. The DFA is pumped using a semiconductor laser and has the advantage that it can be spliced directly into a fiber system, avoiding significant coupling losses. Since the fluorescence lifetime of erbium is long (>10 ms), low distortion performance can be maintained for modulation frequencies down to the GHz region [4].

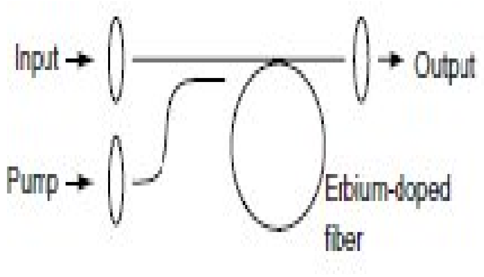


Figure 4.2 Erbium doped fiber

4.3 SIMULATION SETUP

Simulation set up for single tone coherent system is shown in figure 4.3. The schematic diagram shows the transmission of single channels for different users at radio frequency over optical fiber. As shown in the schematic four users are assigned four different step signal at different frequencies and all four user’s data are transmitted by carrier and this carrier are type of radio carrier which having frequency of radio range. In the diagram one sinusoidal generator is generating radio frequency and this frequency is combined with bias wave signal in a combiner. Sinusoidal wave generator is used to generate a signal of 1 GHz frequency. This signal is fed to four different combiners where another signal coming from the bias wave generator is also combined. Four different electrical combiners are used to combine these signals. Four electrical filters are applied to achieve a 3 db gain to different signals coming from combiners. These electrical signals are modulated and converted into optical signal by using rate equation lasers. The center emission wavelengths of all different lasers are set to different wavelength in a range of 1549.5nm to 1550.5 nm. Then these signals are combined with the help of an optical combiner. Then fixed gain optical amplifier is used with 16 dB gain to amplify the signal and then this signal is passed through an optical fiber having a 100 Km distance.

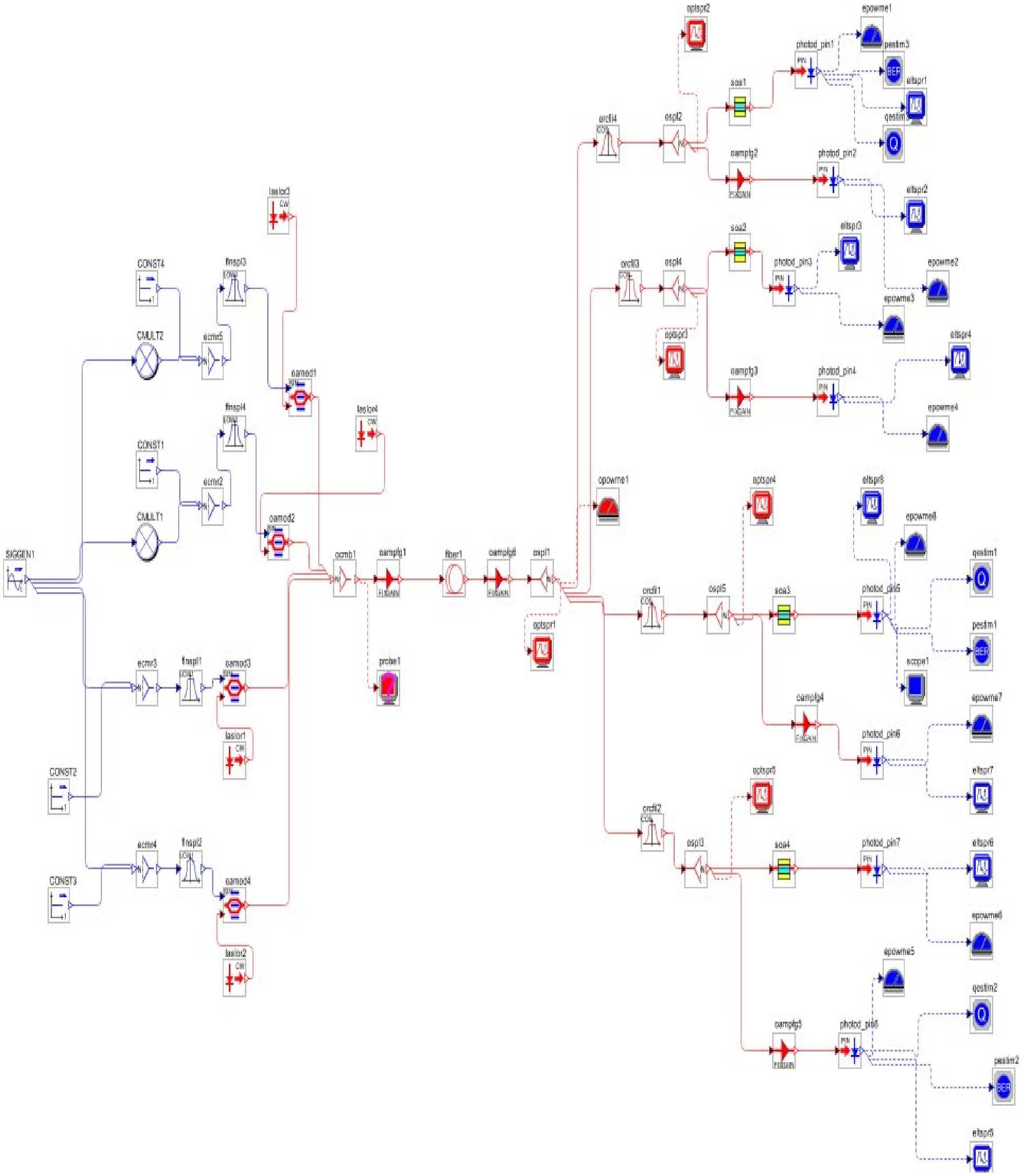


Figure 4.3 Simulation setup for single tone microwave over fiber communication system using coherent system

Now at the receiver side again the output of the optical fiber is amplified by the same type of the optical amplifier and output of the optical amplifier are splitted to four different users with the help of optical splitter.

As some noise is always present in the transmission so to rectify the noise in form of error a Bessel filter is used for each specific user. Now opposite process starts at the receiver side, the light signal is converted in the electrical form. Before electro-conversion this optical signal is passed through a splitter and it split into two signal in which one signal is passed through the EDFA amplifier and photo-detector, while the other signal is passed SOA amplifier and then receiver.

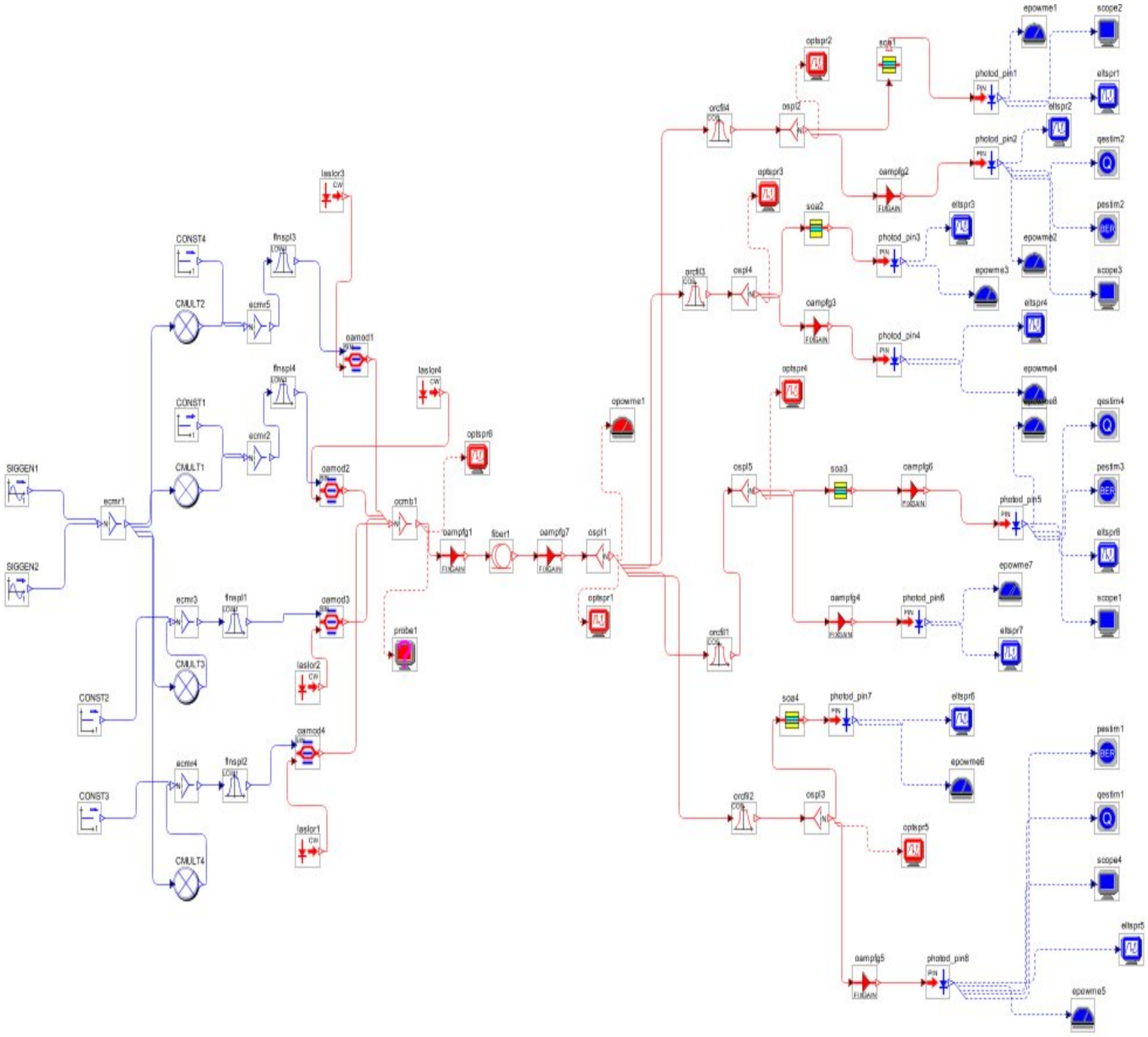


Figure 4.4 simulation setup for multi tone microwave over fiber communication system using coherent system

Figure 4.4 shows the simulation setup for multi tone microwave over fiber communication system using coherent system. The system characteristics are the same as the previous single tone setup. In this case, however, two modulating tones are employed. The frequency of one tone is varied from 1 to 20 GHz through parametric runs, while the other one is fixed at 5 GHz. The simulation setup for multi tone microwave over fiber communication system is shown in figure 4.4. Different users are assigned different step signal at different frequencies and all four user's data are transmitted by carrier and this carrier are type of radio carrier which having frequency of radio range. In the diagram two sinusoidal generators are generating radio frequency and these frequencies are combined with a combiner. So this combiner produces an intermediate frequency. This intermediate frequency is separately used by four different users and this intermediate frequency acts as a carrier for all users separately. Now carrier frequency and user frequency are combined separately at different combiner and the output of the combiner are followed by a Bessel filter which passes only required frequency to which each user assigned, now each user having a different frequency and this radio frequency are modulated by external MZ modulator. MZ modulator consists two input port in which one of the user input while of the other is laser input and this converted electrical signal into the light signal. As this chapter considers about the different user uses separate channels on the same fiber but before transmission the output of the MZ modulator is amplified by a constant EDFA amplifier and the transmitted over the optical fiber. Now at the receiver side again the output of the optical fiber is amplified by the same type of the optical amplifier and output of the optical amplifier are splitted to four different users. The receiver characteristics are the same as single tone microwave over fiber communication system.

4.4 RESULT AND DISCUSSION

In this section transmission of radio frequency over optical fiber is discussed. Four users are of different step signals are combined with carrier radio frequency and transmitted over the fiber transmission, so simulation is done for different frequencies for different users and different waveforms are observed. BER by varying frequency is calculated and other spectrums are observed and further in future users are capable of using high frequencies.

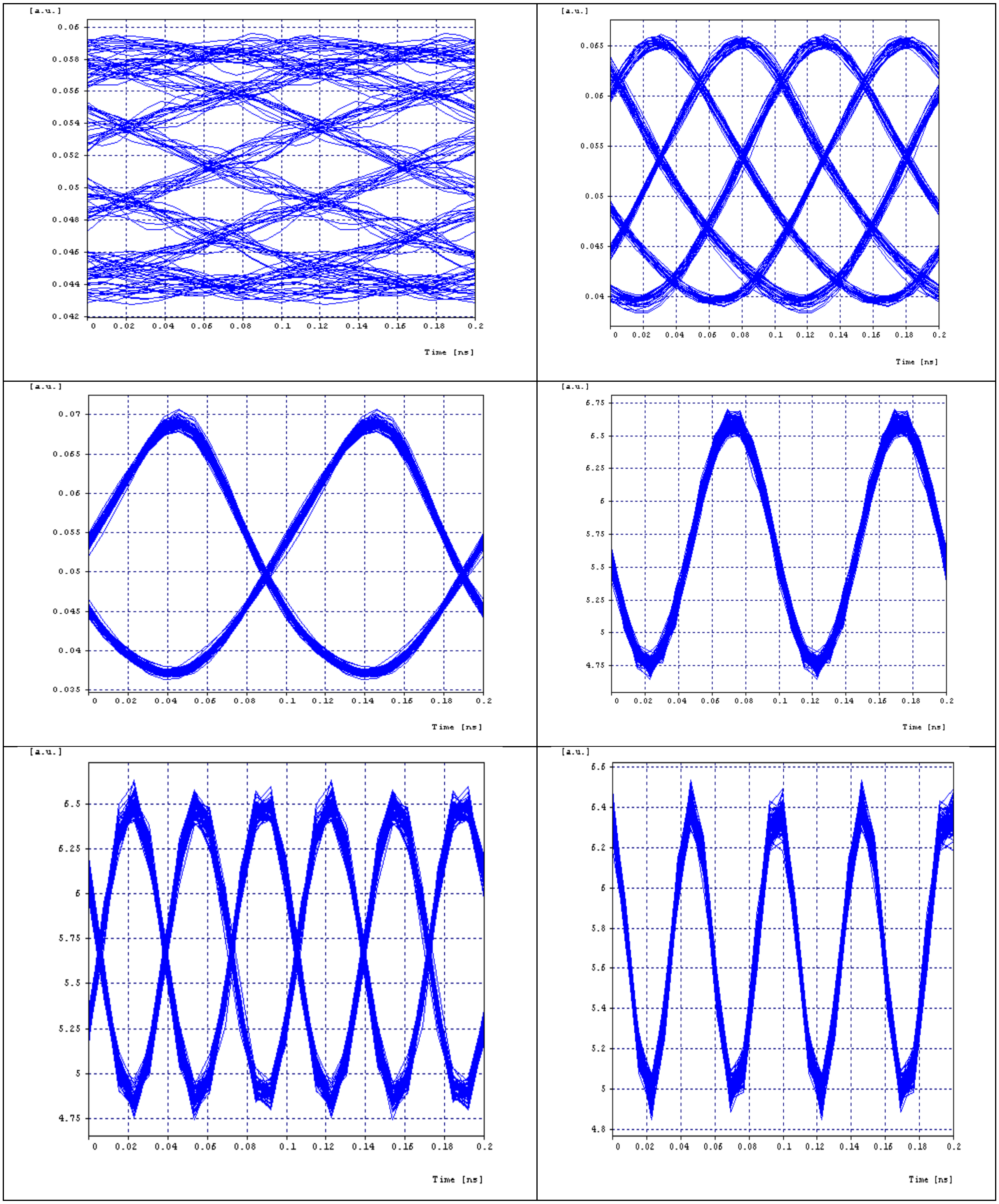
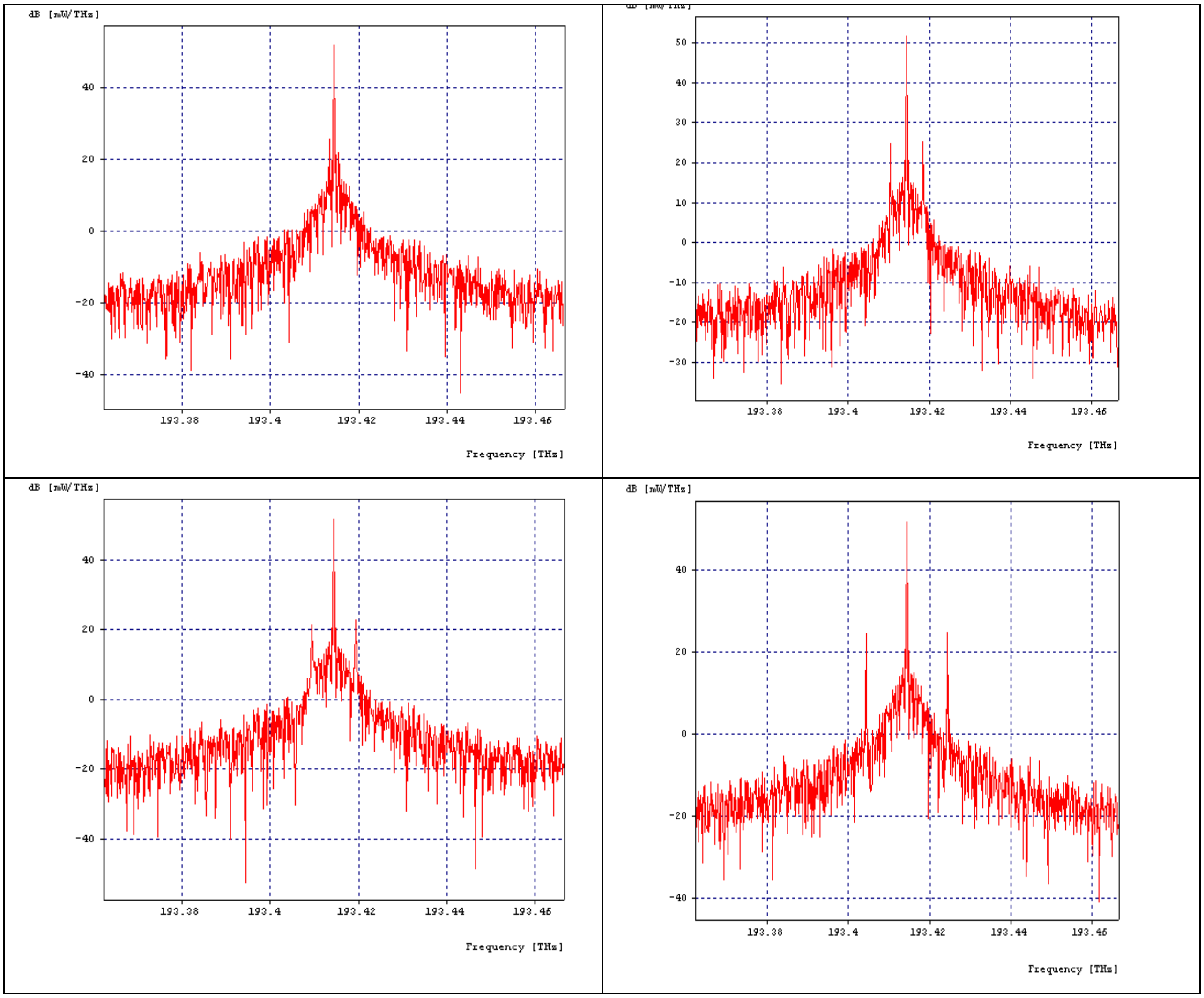


Figure 4.5 Eye diagram of single tone microwave over fiber communication system using coherent at 1, 4, 5, 10, 15, and 20 GHz frequencies

The figure 4.5 shows the eye diagrams of single tone microwave over fiber communication system using 4 users at different frequencies. It can be analyzed that the eye opening at 5 GHz is more than other frequencies. Maximum noise is present at 1, 4, 10, 15 and 20 GHz frequency and also there is noticeable noise at other frequency except 5 GHz. So the users can use 5 GHz frequency spectrum to send their data. The properties of all other component like Bessel filter, EDFA, wave generator are designed to operate at 5 GHz region. Hence, at 5 GHz frequency gives the best performance to operate single tone microwave over fiber communication system.



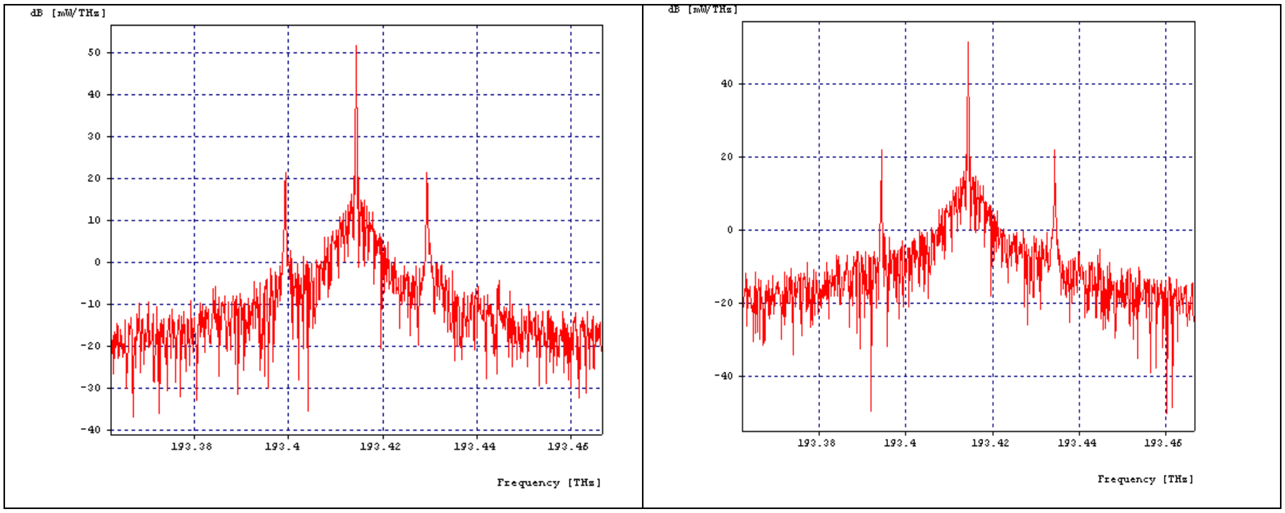
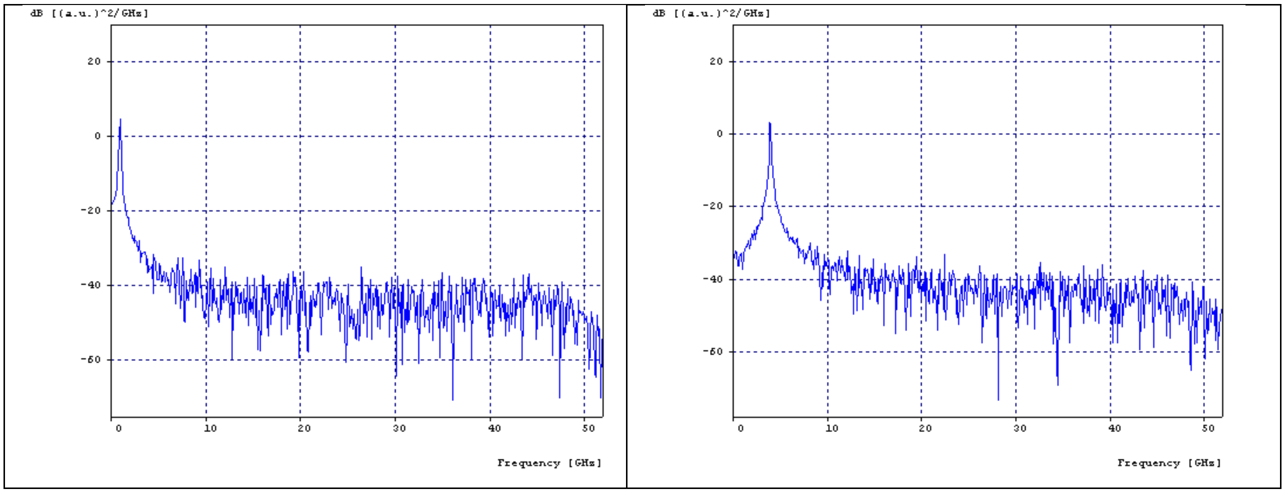


Figure 4.6 Optical spectrum of single tone microwave over fiber communication system using 4 users at 1, 4, 5, 10, 15, and 20 GHz frequencies

The above figure 4.6 shows the optical spectrum of single tone microwave over fiber communication system using 4 users at different frequencies. As shown in eye diagram, the distortion increases as the frequency increase. So we have very less distorted diagram at 5 GHz as compare to distorted optical spectrum at 20 GHz.



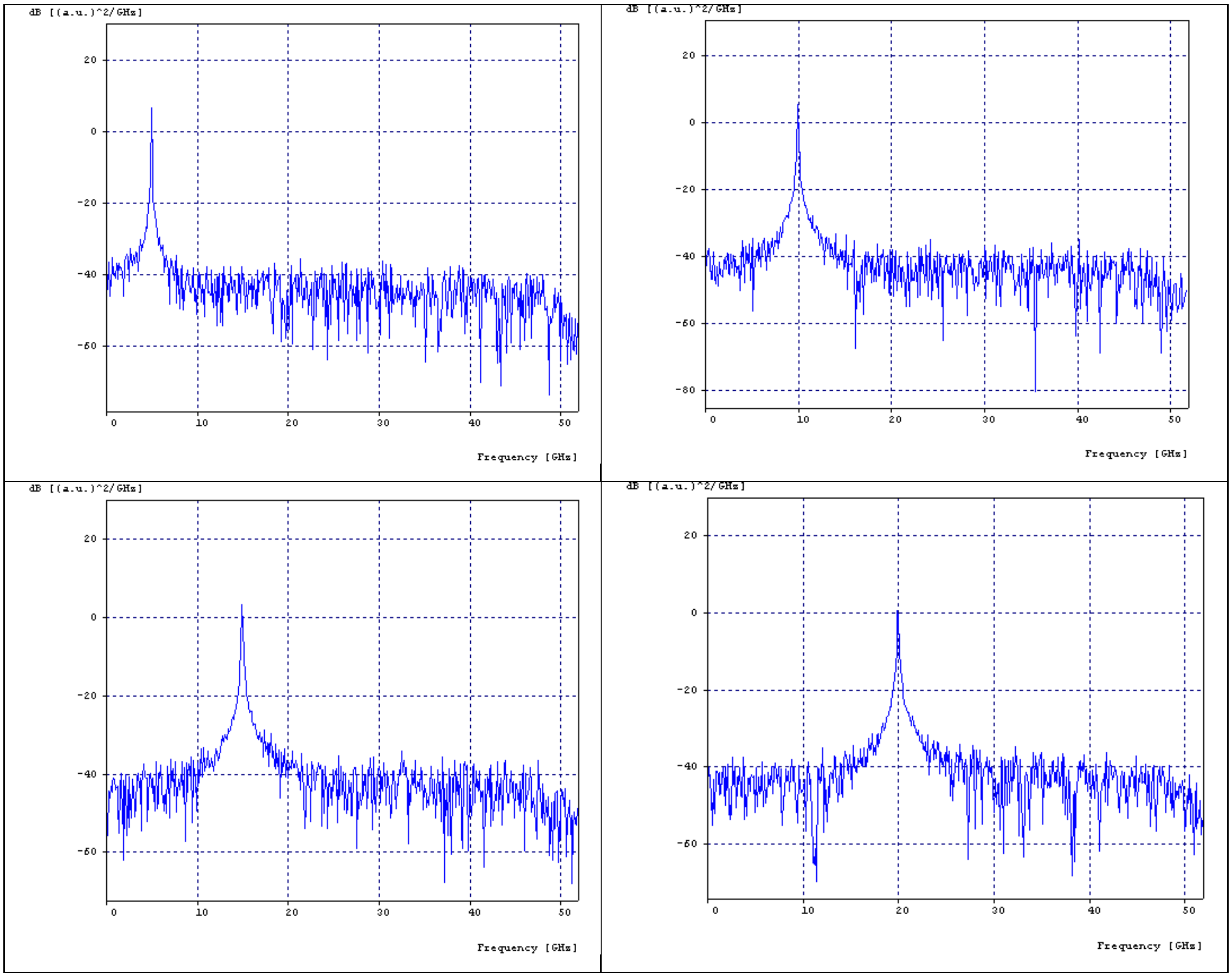


Figure 4.7 Electrical spectrum of single tone microwave over fiber communication system using 4 users at 1, 4, 5, 10, 15, and 20 GHz frequencies

The figure 4.7 shows the electrical spectrum of single tone microwave over fiber communication system using 4 users at different frequencies. It can be analyzed that distortion increases as the frequency increase, which is also shown in eye diagrams and optical spectrum. So we have very less distorted diagram at 5 GHz as compare to distorted optical spectrum at 20 GHz.

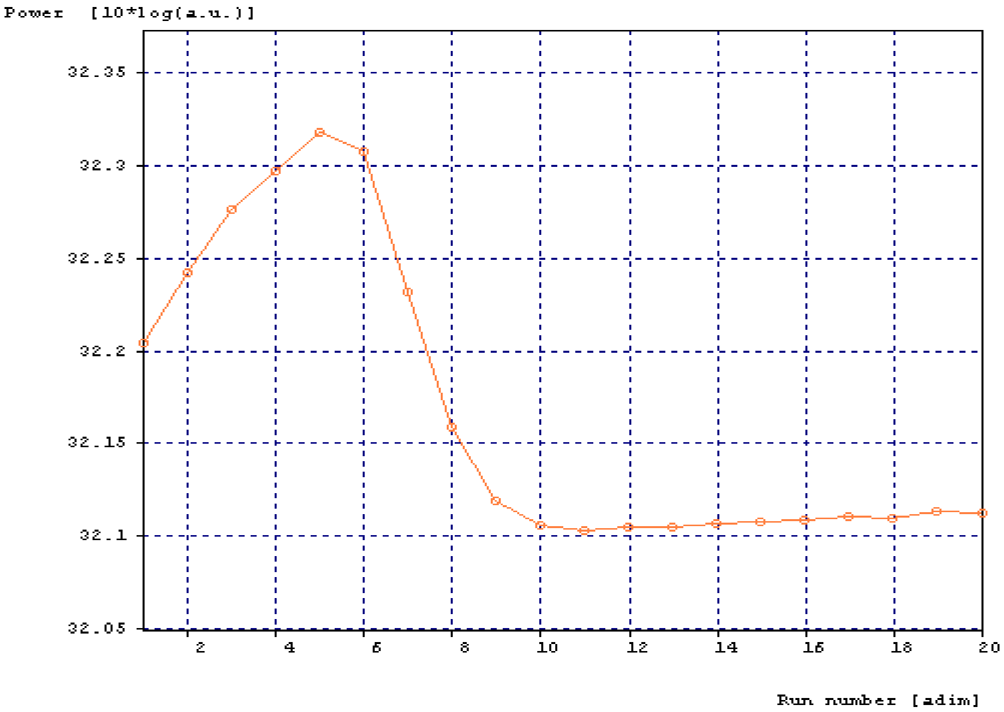


Figure 4.8 The correlation diagram of power Vs frequency for single tone microwave over fiber communication system using coherent system at 1 to 20 GHz frequency range

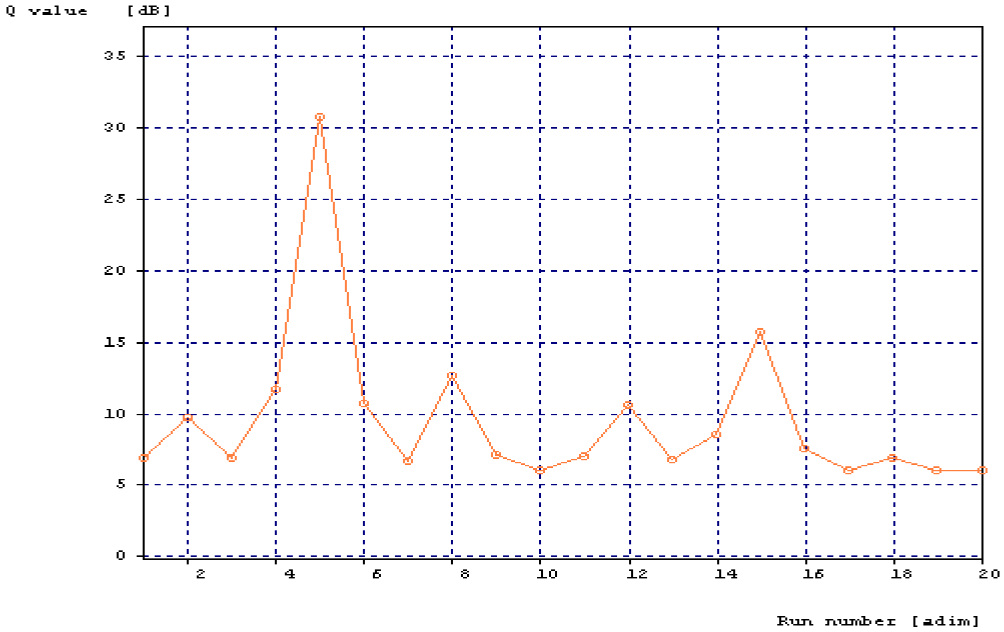
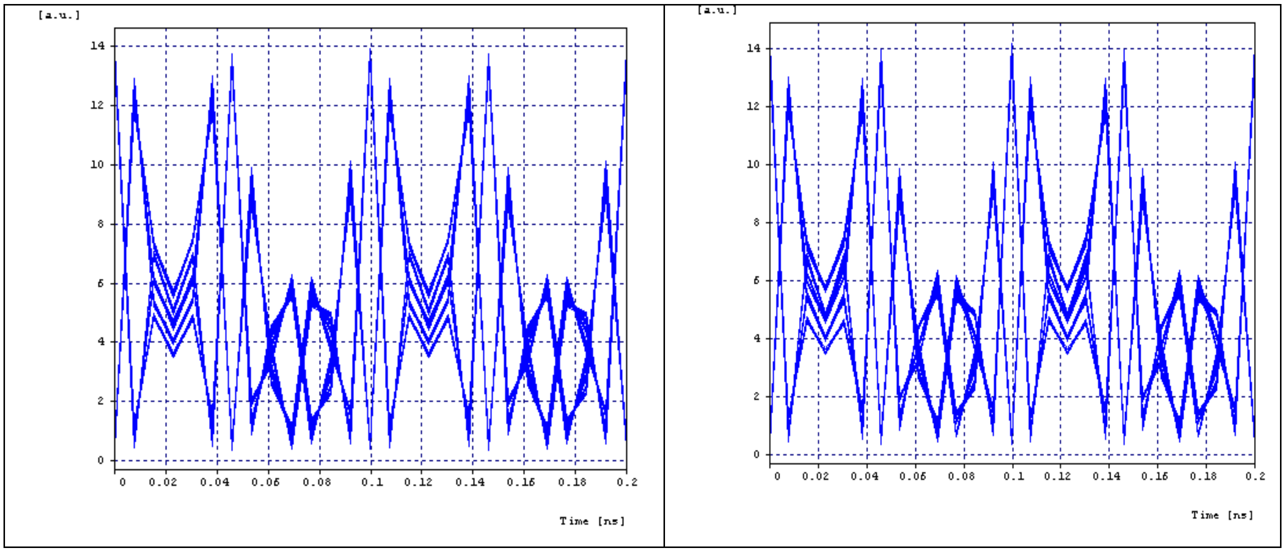


Figure 4.9 The correlation diagram of Q parameter Vs frequency for single tone microwave over fiber communication system using coherent system at 1 to 20 GHz frequency range

Figure 4.8 shows a correlation diagram of power Vs frequency for single tone microwave over fiber communication system using 4 users. A frequency range from 1 GHz to 20 GHz is taken in this diagram. It is analyzed that the maximum power is achieved at 4-5 GHz frequency band. But at other frequencies, the power is less. If we increased the frequency above 10 GHz, then the power level is very low and is not sufficient to transmit the data and with increase in frequency, the value of power level is decreased. So, the 5 GHz frequency is best suitable for transmitting data in single tone microwave over fiber communication system.

Figure 4.9 shows a correlation diagram of Q parameter Vs frequency for single tone microwave over fiber communication system using 4 users. A frequency range from 1 GHz to 20 GHz is taken in this diagram. It is analyzed that the maximum value of Q is achieved at 5 GHz frequency. But at other frequencies, the value is less. It can be seen that the maximum Q is achieved at 4 to 5 GHz frequency range. Hence with increase in frequency, the value of Q is decreased. So, the 5 GHz frequency range is the best suitable for transmitting the data.



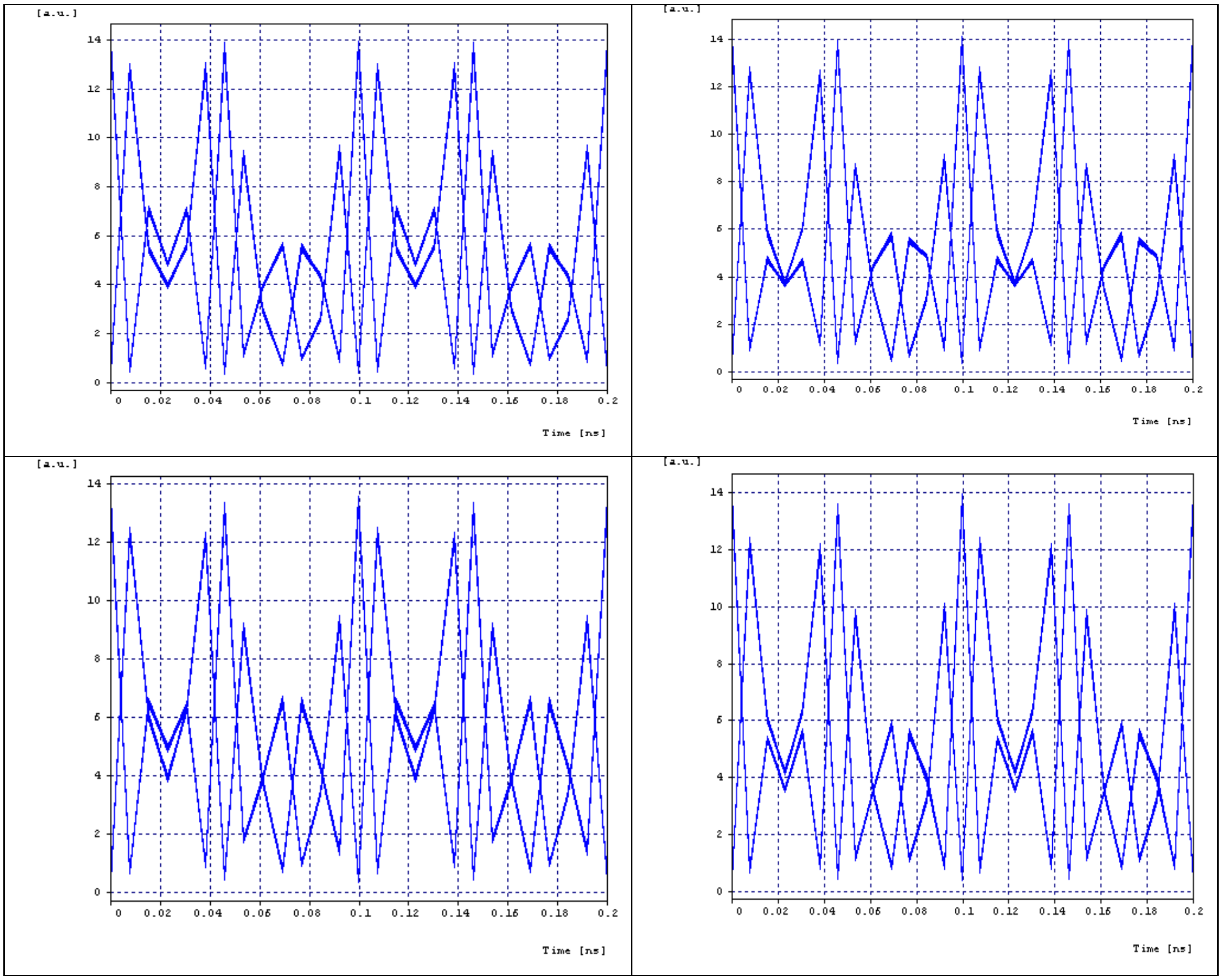


Figure 4.8 Eye diagram of multi tone microwave over fiber communication system using 4 users at 1, 4, 5, 10, 15, and 20 GHz frequencies

The above figure 4.8 shows the eye diagrams of multi tone microwave over fiber communication system using 4 users at different frequencies. It can be analyzed that the noise at 5 GHz is less than other frequencies. Maximum noise is present at 1, 9 and 11 GHz frequency and also there is noticeable noise at other frequency except 5 GHz. So the users can use 5 GHz frequency spectrum to send their data. The properties of all other component like Bessel filter, EDFA, wave generator are designed to operate at 5 GHz region. Hence, at 5 GHz frequency gives the best performance to operate single tone microwave over fiber communication system.

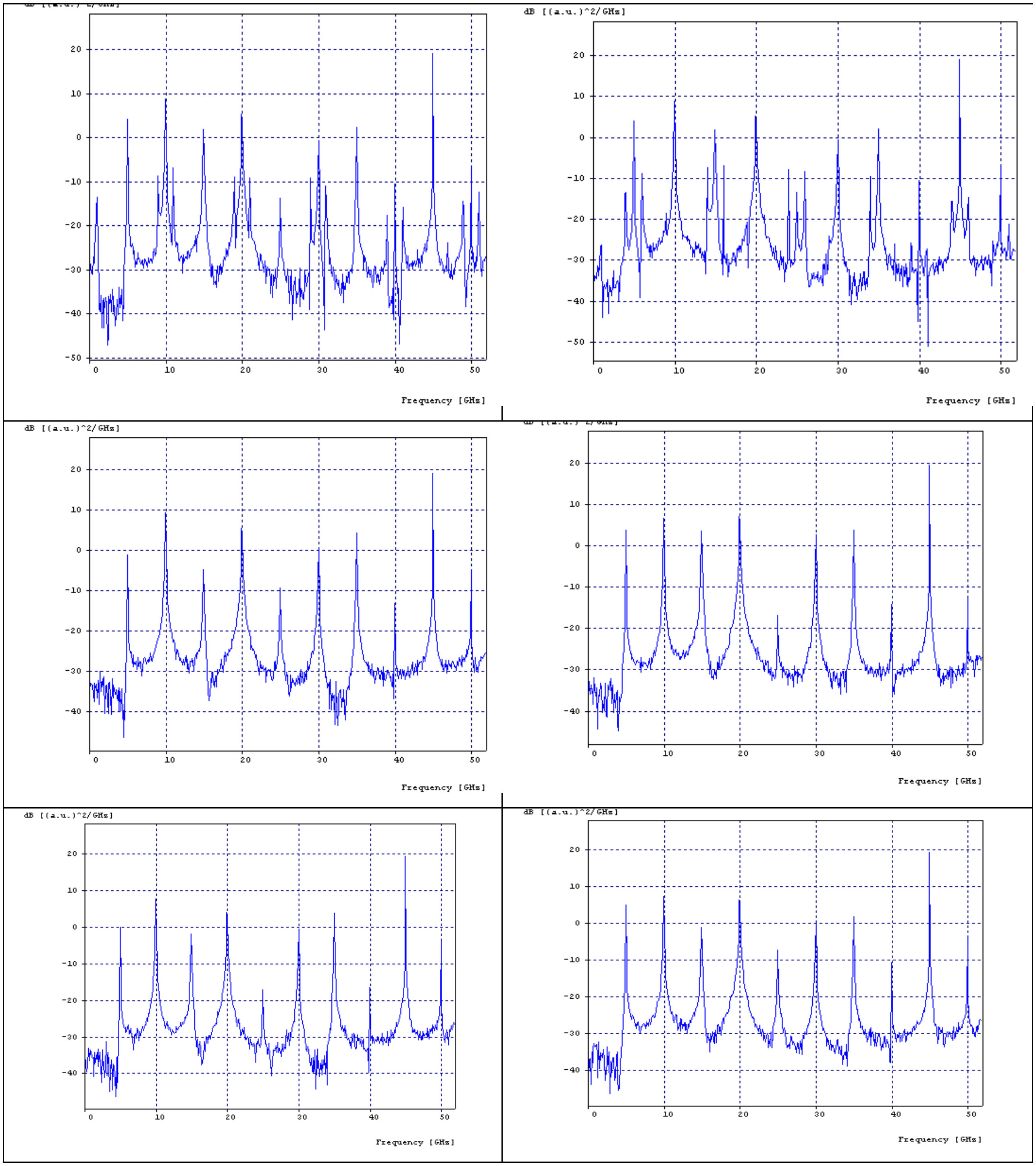


Figure 4.9 Electrical spectrum of multi tone microwave over fiber communication system using coherent system at 1, 4, 5, 10, 15, and 20 GHz frequencies

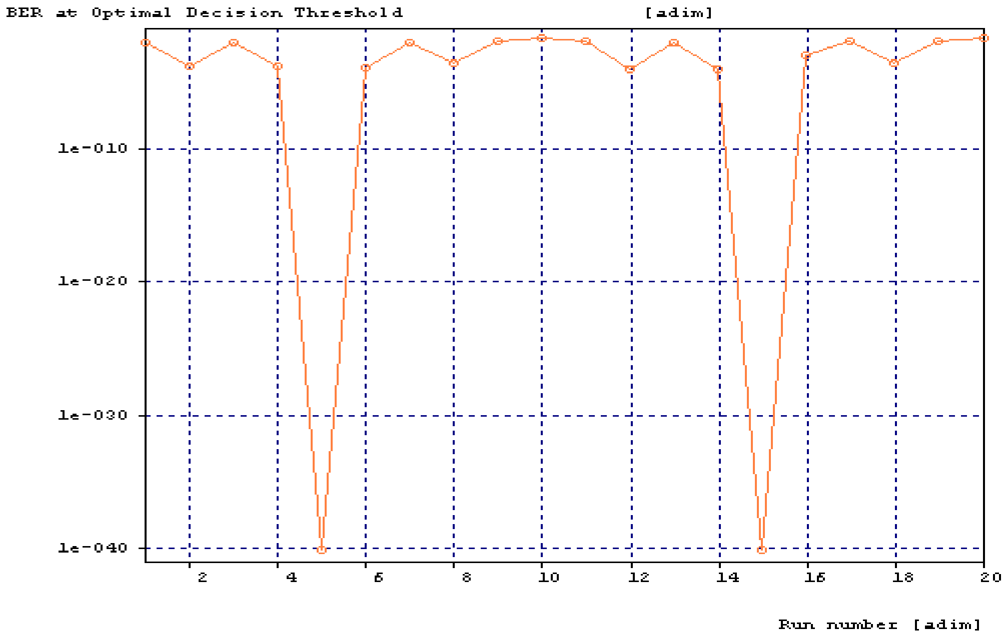


Figure 4.10 BER Vs frequency diagram of multi tone microwave over fiber communication system using coherent system at 1, 4, 5, 10, 15, and 20 GHz frequencies

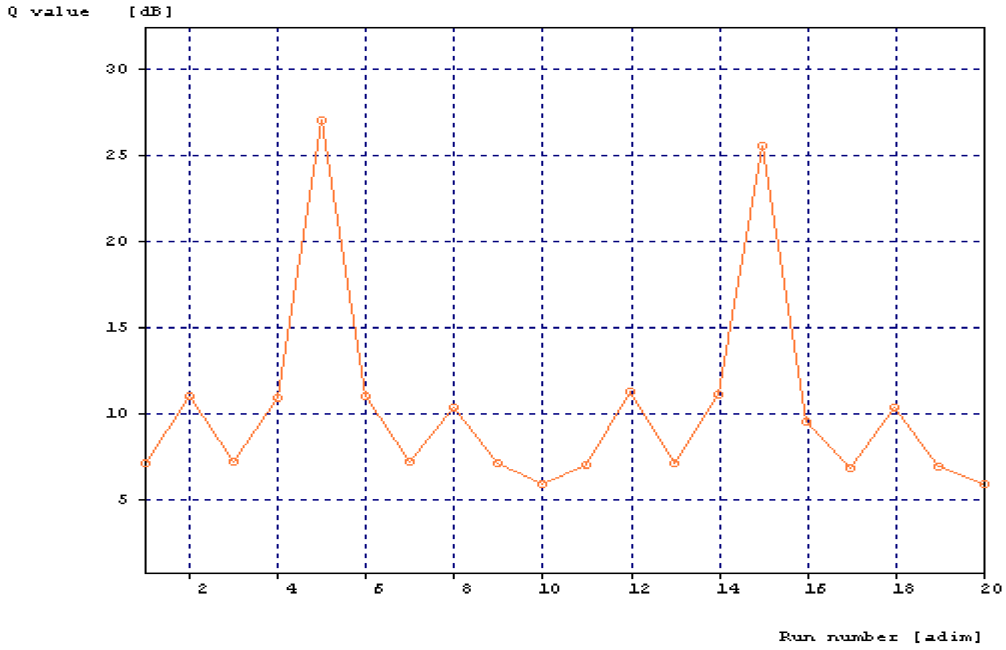


Figure 4.11 The correlation diagram of Q parameter Vs frequency for multi tone microwave over fiber communication system using coherent system at 1 to 20 GHz frequency range

The above figure 4.9 shows the electrical spectrum of multi tone microwave over fiber communication system using 4 users at different frequencies. It can be analyzed that distortion increases as the frequency increase, which is also shown in eye diagrams and optical spectrum. So we have very less distorted diagram at 5 GHz as compare to distorted optical spectrum at 20 GHz.

Figure 4.10 shows BER diagram for multi tone microwave over fiber communication system using 4 users at 1 to 20 GHz frequency range. It is analyzed that there is negligible BER at near 5 and 15 GHz frequency band. Hence for transmission of different data we can use these two bands.

Figure 4.11 shows a correlation diagram of Q parameter Vs frequency for multi tone microwave over fiber communication system using 4 users. A frequency range from 1 GHz to 20 GHz is taken in this diagram. It is analyzed that the effective q is achieved at two frequency ranges i.e. 4 to 5 and 14 to 15 GHz frequency band. But at other frequencies, the value is less. So, these two frequency bands are best suitable for transmitting data in single tone microwave over fiber communication system.

4.5 CONCLUSION AND FUTURE SCOPE

The low-loss, wide-bandwidth capability of optical transmission systems makes them attractive for the transmission and processing of microwave signals, while the development of high-capacity optical communication systems has required the import of microwave techniques in optical transmitters and receivers. These two strands have led to the development of the research area of microwave photonics. Among the applications reviewed are wireless-over-fiber access systems, broadband signal distribution and access systems, and communications antenna remoting systems. In this paper, a microwave over fiber communication system using coherent system (external modulator) is reported. It has been shown that two system, single tone and multi tone can be recommended for microwave over fiber communication systems. From the eye diagrams, bit error rate (BER) and the Q-factor characteristics, it is clear that the single tone microwave system gives best performance at 5 GHz frequency for single tone system. By using multi tone various types of data can be transmitted at 5 GHz and 15 GHz frequency band. It is also analyzed that the output taken from EDFA is better than SOA. This is because EDFA amplifies all the frequencies simultaneously.

A number of research groups challenged optical transmission experiments with coherent receivers. However, the invention of erbium-doped fiber amplifiers (EDFAs) made the shot-noise limited receiver sensitivity of the coherent receiver less significant. This is because the signal-to-noise ratio (SNR) of the signal transmitted through the amplifier chain is determined from the accumulated amplified spontaneous emission (ASE) rather than the shot noise. In addition, even in unrepeated transmission systems, the EDFA used as a low-noise preamplifier eliminated the need for the coherent receiver with superior sensitivity. Technical difficulties inherent in coherent receivers could not also be disregarded. Rapid progress in EDFA technologies entirely changed the direction of R&D in optical communications.

CHAPTER 5

THE LOSS LESS AND DISPERSION MANAGED SOLITON TRANSMISSION SYSTEM

In this chapter, a lossless and dispersion-less soliton in a fiber link is analyzed. A dispersion compensated fiber and a periodical amplification is done to increase the efficiency of the soliton. To achieve a lossless soliton, the group velocity dispersion (GVD) parameter is required to be constant along the fiber length. But it is difficult to achieve a constant GVD parameter, so dispersion compensated fiber is used for increasing the efficiency of the soliton fiber link. This kind of solitons is called dispersion-managed solitons. Modern WDM light-wave systems employ dispersion management to compensate for cumulative dispersion and to suppress FWM penalties. A circulating loop is used which is consist of three regular fiber spans, one dispersion-compensating fiber (DCF) span, optical filter and EDFA optical amplifier. The system transmits the data up to 9000 km. It is shown that the pulse spectrum is broadening due to the high-order soliton effect and third- order dispersion near the zero dispersion wavelength, the spectrum begin to be shaped by optical filter installed at the end of the loop which removes the unwanted spectral peak that gets created on the left hand side of the spectrum.

5.1 INTRODUCTION

Recently, many researchers have been developed to transmit soliton for long distances with the use of erbium-doped fiber amplifiers [41]. Synchronous modulation with optical filters allows for unlimited-distance soliton transmission because evolution of noise is suppressed [53]. The stable soliton transmission can be achieved over 10,000 Km by reducing noise as used in sliding frequency filter technique [69]. A soliton is a self-reinforcing solitary wave of permanent form which does not change its shape while travelling at constant speed. These waves are caused by a cancellation of nonlinear effects of medium. The frequency and the speed of the waves also affect the behavior of the soliton. The first phenomenon about soliton was given by John Scott Russell (1808–1882) who observed a solitary wave in the Union Canal in Scotland. He reproduced the phenomenon in a wave tank and named it the "Wave of Translation" [36].

Gordon et al. [40] showed that the statistics of the jitter due to spontaneous emission noise added by the lumped amplifiers is Gaussian with a variance proportional to the cube of the total distance of the links. For long-haul light wave transmission links Soliton communication systems are leading candidates. Dispersion and non-linearity can interact to produce permanent and localized wave forms. Consider a pulse of light traveling in glass. This pulse can be thought of as consisting of light of several different frequencies. Since glass shows dispersion, these different frequencies will travel at different speeds and the shape of the pulse will therefore change over time [39]. The soliton balances along its path between the dispersive and nonlinear terms of the non-linear Schrodinger equation [37]. The ideal soliton can exist in a lossless fiber with a balance between the chirp induced by fiber GVD and fiber nonlinearity characterized by self-phase modulation (SPM) [38].

John Scott Russell et al. [36] described the wave of translation. The motion of a boat which was rapidly drawn along a narrow channel by a pair of horses was observed. The first idea about the soliton was given in this. The soliton waves, their properties and comparison of these waves with normal sea waves were investigated. It was stated that unlike normal waves the soliton waves never merge and the speed depends on the size of the wave, and its width on the depth of water.

E. Kengne et al. [49] demonstrated a class of dissipative complex Ginzburg–Landau (DCGL) equations that govern the wave propagation in dissipative nonlinear transmission lines. Two soliton solutions of the DCGL equations, from which the one-soliton solutions were deduced, were obtained in analytical form. The modified Hirota method imposed some restrictions on the coefficients equations. Namely, the second-order dispersion was real. The physical requirement of the solutions imposed complementary conditions on the combination of the dispersion and nonlinear gain/loss terms of the equation, as well as on the coefficient of the Kerr nonlinearity. The analytical solutions for one solitary pulse were tested in direct simulations.

Hirokazu Kubota et al. [50] presented new soliton transmission method with lumped amplifiers. A new possibility for long-distance soliton propagation with the pre-emphasis method was shown. For a given amplifier spacing, by increasing the input pulse intensity up to a maximum of 1.4, the pre-emphasis method was very successful in sending solitons over long distances.

M. Kumar et al. [51] investigated the performance of first- and second-order path-averaged soliton long-haul transmission link. The impact of third-order dispersion (TOD) at varied chirp had been discussed. The observations established that the pulse width (FWHM) remains within the optimal range without and up to certain discrete values of the chirp factor.

Linn F. Mollenauer et al. [52] showed both analytically and with numerical simulation, that solitons were remarkably resilient to large variations in energy and dispersion, as long as the characteristic length scale of those variations was considerably less than . There was therefore no barrier to the use of lumped amplifiers, nor to the use of practical dispersion shifted fibers, in ultra-long distance communication using solitons.

Many papers on soliton, its theory and wave behavior have been qualitative. Various approaches have been suggested for enhancing the soliton wave properties. But, all the papers are related to solitons behavior. Till now, the efficient transmission through solitons is not possible. There is loss due to non linearity and dispersion. In this chapter, the loss and dispersion management is studied.

This chapter is divided into five modules. In the first module, the brief introduction about the soliton fiber link is presented. In second module a descriptive model for dispersion managed soliton is proposed. The simulation setup is described in third module. The simulation results for the systems have been discussed in the forth module. The fifth module gives the conclusion and future scope.

5.2 DESCRIPTIVE MODEL

In the negative group velocity dispersion (GVD) region of optical fibers, solitons can be generated by balancing self-phase modulation with negative GVD. A soliton is a good information carrier because of its short duration and high stability [50]. The existence of solitons in optical fibers is the result of a balance between the chirps induced by fiber dispersion characterized by GVD (group velocity dispersion) coefficient and fiber nonlinearity characterized by SPM (self-phase modulation) coefficient γ [41]. For long-distance optical transmission systems, optical amplifiers must be used to compensate for fiber loss. Stimulated Raman scattering (SRS) in optical fiber is promising for soliton transmission since it operates as a distributed gain medium [50].

The layout for generation of the solitons is shown in Figure 5.1. It consists of pulse generator (mode-locked laser), single mode lossless fiber, and waveform and spectrum analyzers. The fiber is assumed to be lossless to demonstrate ideal soliton propagation. Fiber dispersion = -20 ps/km/nm. Input signal is generated using data source and an electrical generator, this signal is fed to the external modulator. External modulator has one another input, optical signal fed by

Laser source. This signal is now transmitted through fiber. For a long distance, fiber loop is applied to run for 9000 Km. Optical amplifiers are also after every 30 Km distance. Dispersion compensated fiber (DCF) is applied to managed dispersion. This fiber has a negative value of dispersion so that it can cancel the dispersion having positive value.

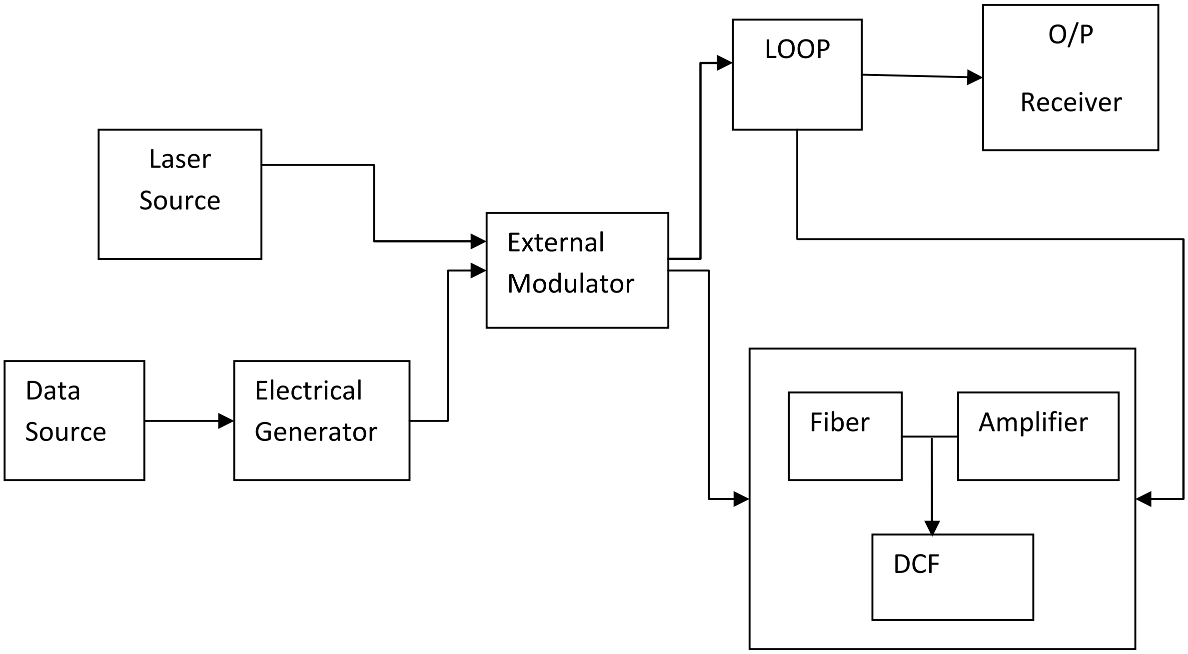


Figure 5.1. Layout for soliton in optical fiber communication system

The transmitted signal is detected at receiver side. Compound optical receiver is used to detect the signal. An amplifier is also used before receiver so that the signal strength can be increased. The output signal from optical signal is now converted in to desire format.

5.3 SIMULATION SETUP

The simulation set up for dispersion managed soliton is shown in figure 5.2. A signal of 10 Gbps is generated with signal generator. This signal is fed to external modulator. A mode locked laser source is used to generate sech pulses. This signal is also connect to the input of external modulator. A Mach- Zender modulator is used to convert the electrical signal in to optical signal. A loop device is applied to repeat the fibers so that a maximum distance can be covered. 3 fiber span of 30 km is used with EDFA amplifiers. Different spectral components of the launched optical pulse travel within the fiber at slightly different group velocities. This spreads the pulse in the time domain producing the effect known as chromatic dispersion (CD). A high negative value is maintained at DCF so that the effect of dispersion can be cancelled by adding positive and negative values of dispersion.

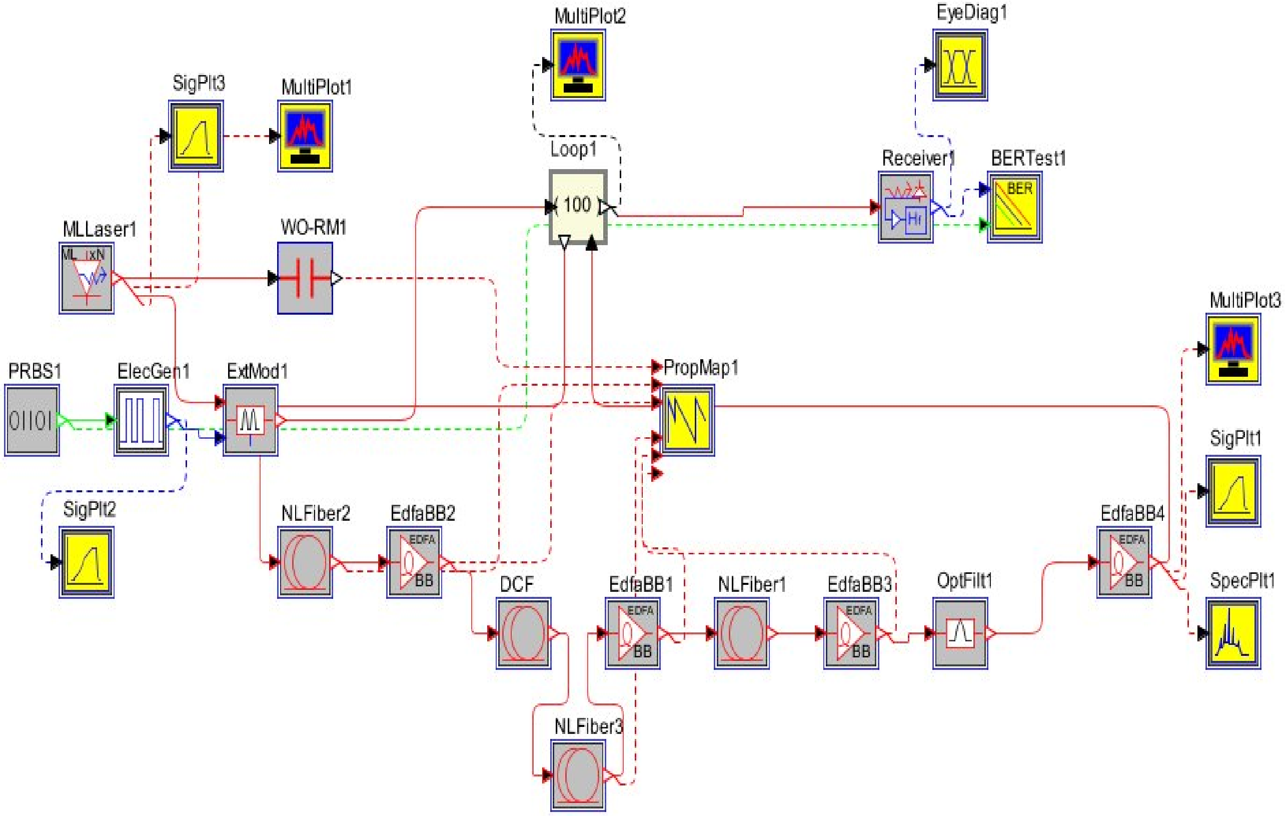


Figure 5.2 Simulation setup for dispersion managed fiber link

Dispersion management in single mode fiber links can be accomplished in many ways, though the most widely used approach employs lengths of transport fiber of opposite dispersion characteristics to the principal fiber in the link, usually standard single mode fiber (SSMF). Typically a 10 to 20km length of dispersion compensating fiber (DCF) is placed before the regenerators inducing negative dispersion to compensate for the positive dispersion accumulated over the 60 to 80km length of the SMF. Although the total dispersion over the entire SMF-DCF span can be minimal, net dispersion at any point along the span is non-zero, which keeps the nonlinear mixing effects at minimum levels.

Pulse will travel total 100 loops or 9,000km. Fibers in a loop are 30-km long with dispersion coefficient 0.2 ps/km/nm at 1550 nm and dispersion slope 0.07 ps/km/ . For three spans total accumulated dispersion is 36 ps/nm. DCF has dispersion –72 ps/km/nm and length 0.5 km, i.e. total dispersion is –36 ps/nm and fully compensates the cumulative dispersion in the loop to zero. DCF is inserted after first two 30-km spans. Fiber loss is 0.22 dB/km and EDFAs after fiber span set to 6.6 dB gain to compensate signal attenuation. The optical filter is placed at the end of the loop and has a width of 2.7 nm. The input pulse is generated by Mode-Locked Laser and has a "sech" shape with 7 ps pulse width. The pulse peak power corresponds to N=1 soliton and is set to 11.56 mW. A number of signal and spectrum analyzers are attached to output from laser, fiber, and amplifiers blocks. Property Map block tapped to outputs of elements in the loop will record pulse dispersion, width, and optical power along the fiber length.

5.4 RESULT AND DISCUSSION

Figure 5.3 shows the dispersion map of a fiber link. In each loop the dispersion reduce to minimum value ~ zero due to dispersion compensated fiber, but since DCF is inserted non-symmetrically, after second out of three fiber spans, the average dispersion is small but non-zero, equal to -6 ps/nm.

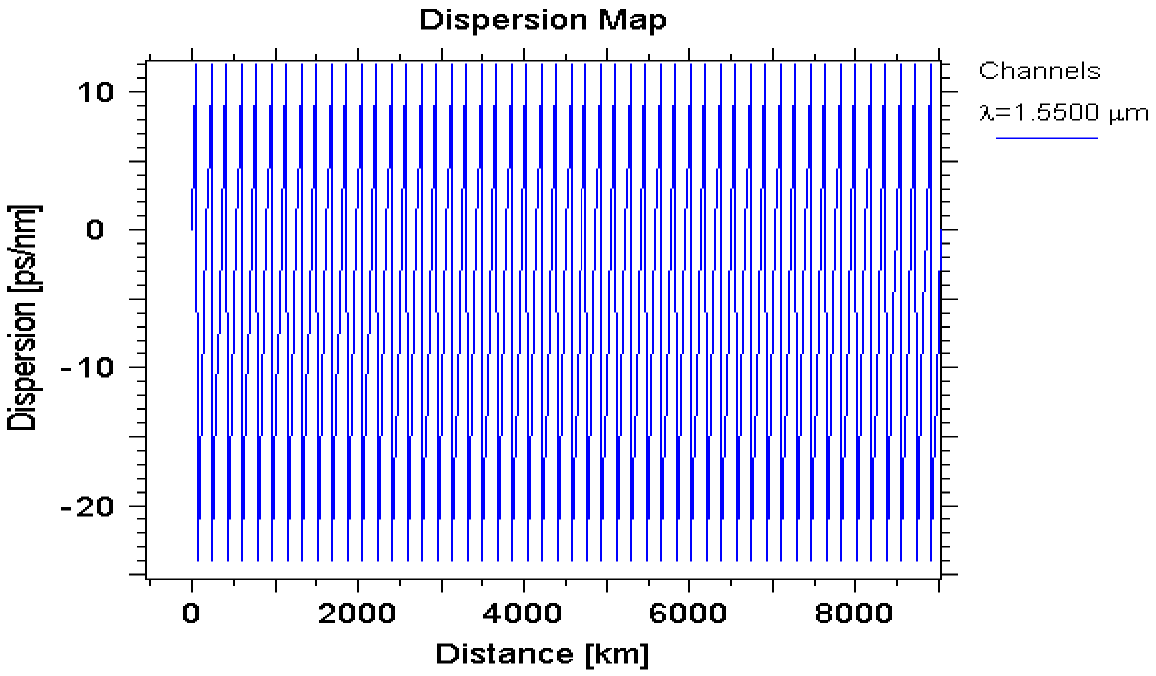


Figure 5.3 Dispersion Vs distance

Non-zero local dispersion helps to reduce FWM penalties. Figure 5.4 shows the pulse width evolution vs distance. A pulse of 7 ps starts at initial value, then oscillating with amplitude going up to 3o ps, and after about 2,000 km the pulse width decreases and touch a value less than 3ps. After 4000 Km it converges to steady-state with pulse width changing periodically between 6 and 13 ps within each loop.

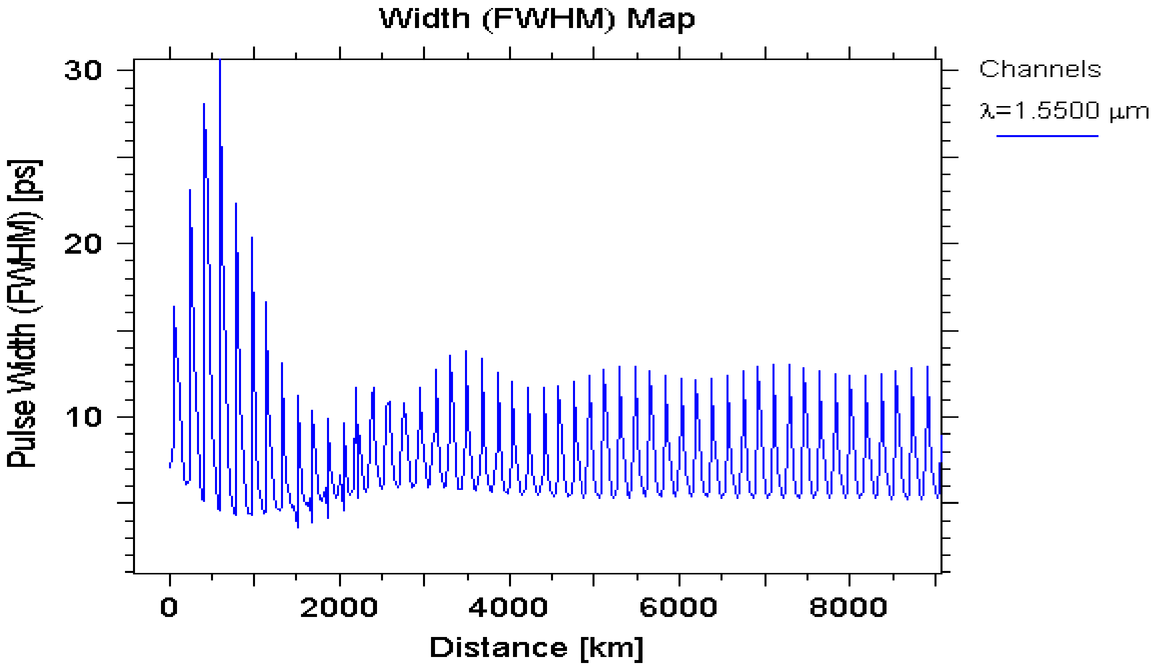


Figure 5.4 Pulse width Vs distance

Figure 5.5 shows the chirp of output signal. Input soliton pulse first travels 60 km of anomalous dispersion fiber supporting soliton propagation, but then DCF nonlinearity broadens the soliton pulse into a rectangular pulse with a linear chirp. This up-chirped pulse is coupled into next 30-km long fibers with anomalous dispersion. Because the pulse after passing through first 60-km is up-chirped and broadened, the pulse is linearly compressed by the anomalous dispersion and a high-order soliton is excited in the next 180-km fiber. This results in large spectral broadening and soliton narrowing. When the pulse spectrum is broadening due to the high-order soliton effect and third-order dispersion near the zero dispersion wavelength, the spectrum begin to be shaped by optical filter installed at the end of the loop which removes the unwanted spectral peak that gets created on the left hand side of the spectrum.

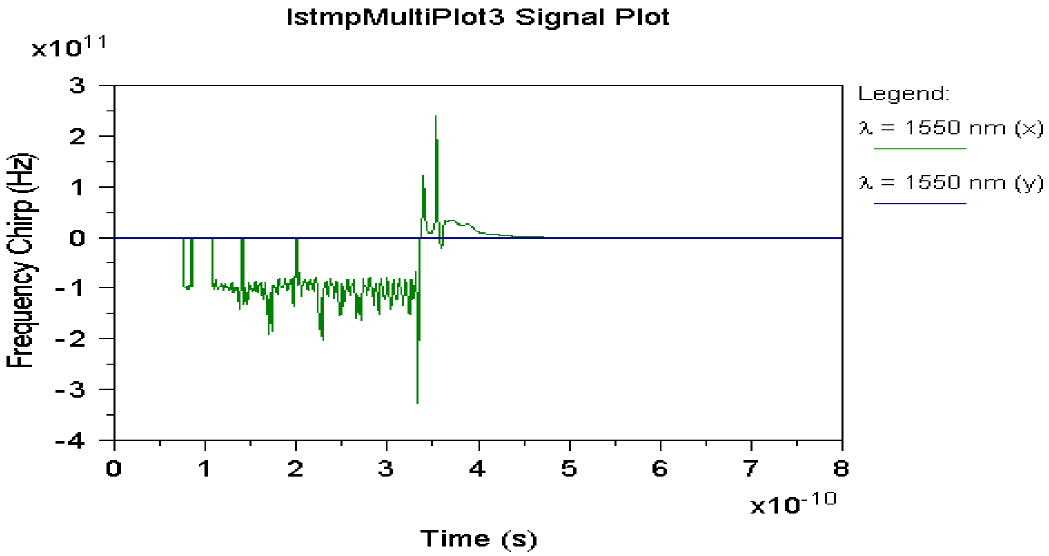


Figure 5.5 Frequency chirp in output

Figure 5.6 shows the pulse power evolution. It starts with -16 dBm to – 9 dBm range. After travelling 1000 Km i.e. traveling a few first loops, it decreases up to – 17 dBm to -10 dBm. A quasi-steady-state behavior of power pulse is obtained after travelling a 2000 Km distance.

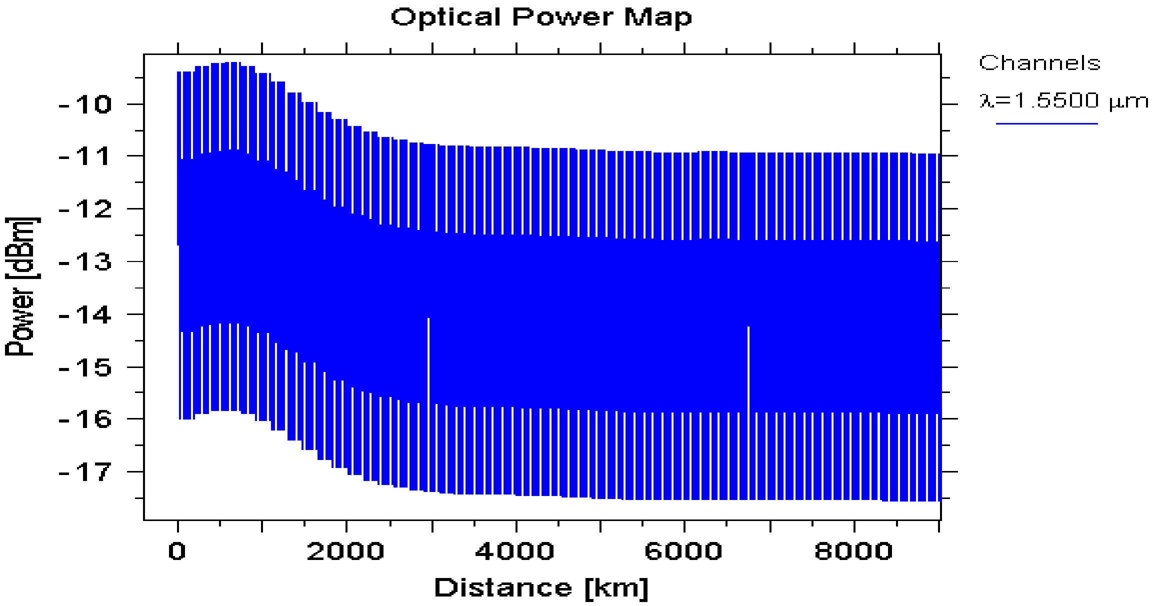


Figure 5.6 Pulse power evolution

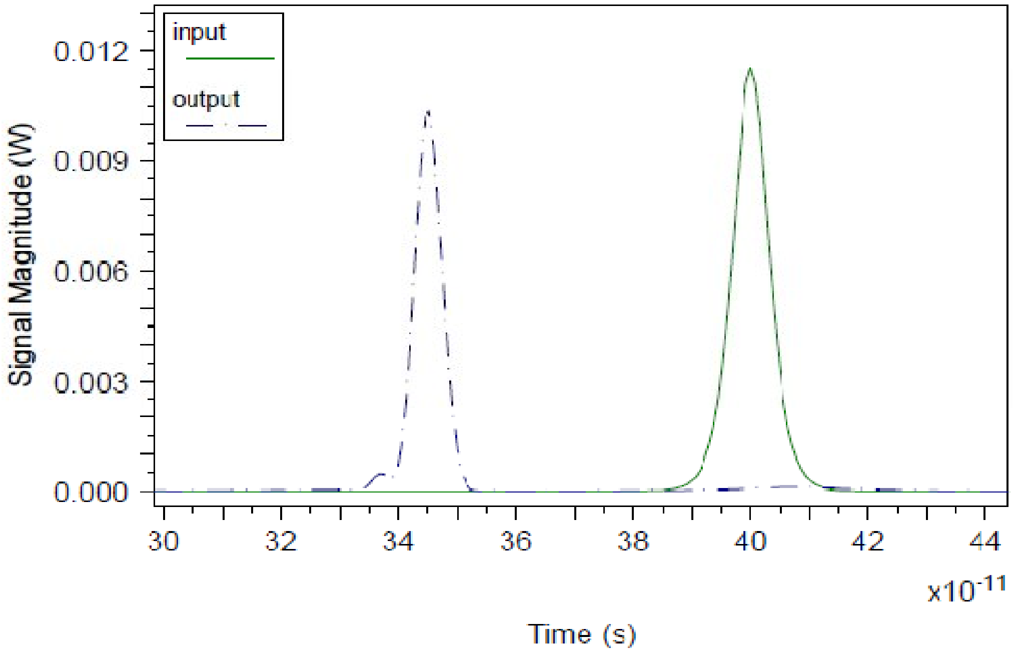


Figure 5.7 Input and output after 9000 Km pulse waveform

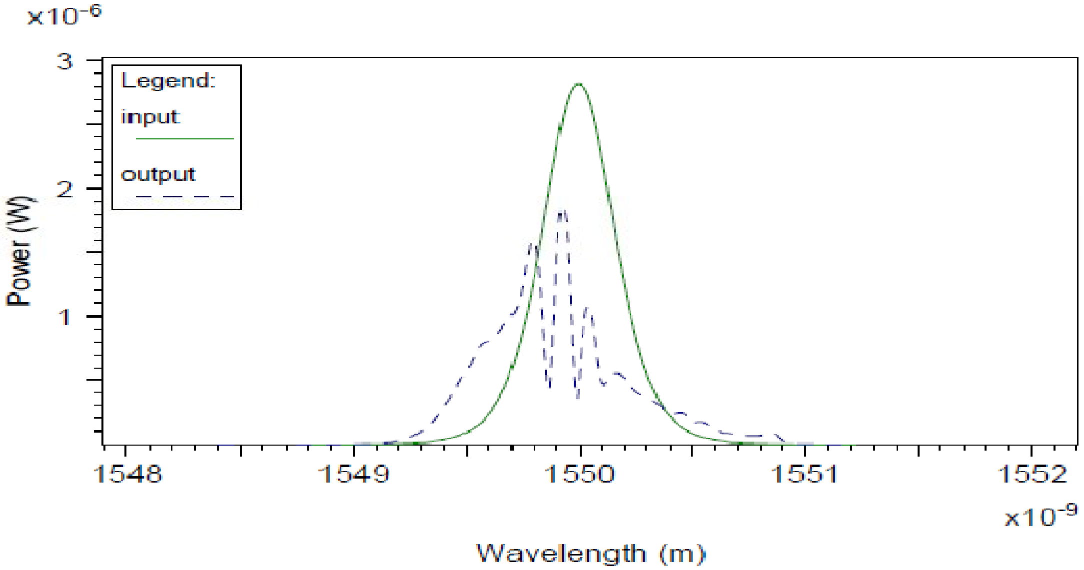


Figure 5.8 Input and output after 9000 Km optical spectrum

Figure 5.7 and 5.8 show pulse waveform and corresponding spectrum for input and output pulse after 100 loops, respectively.

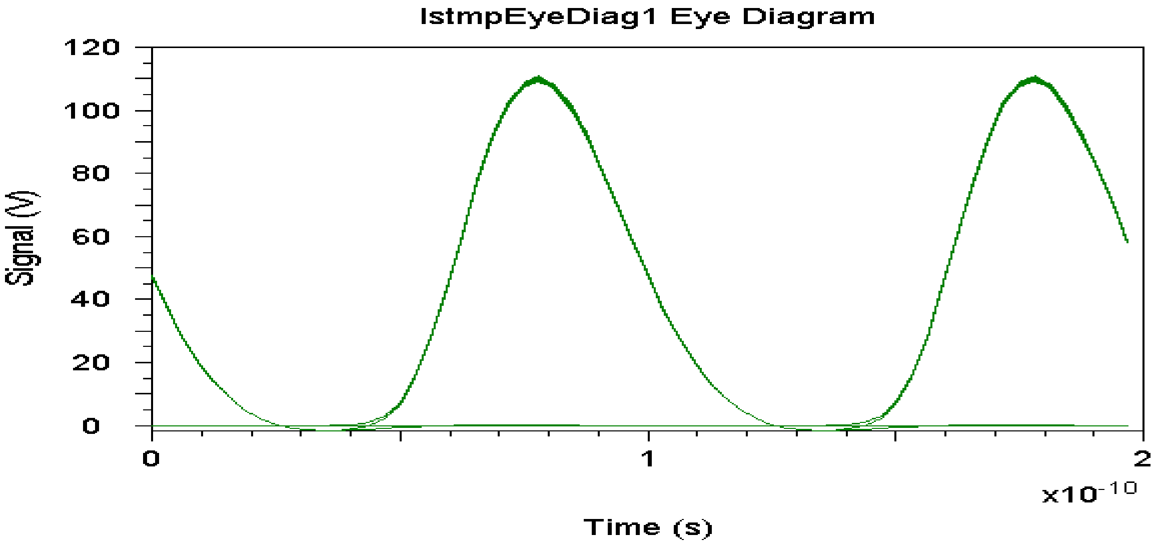
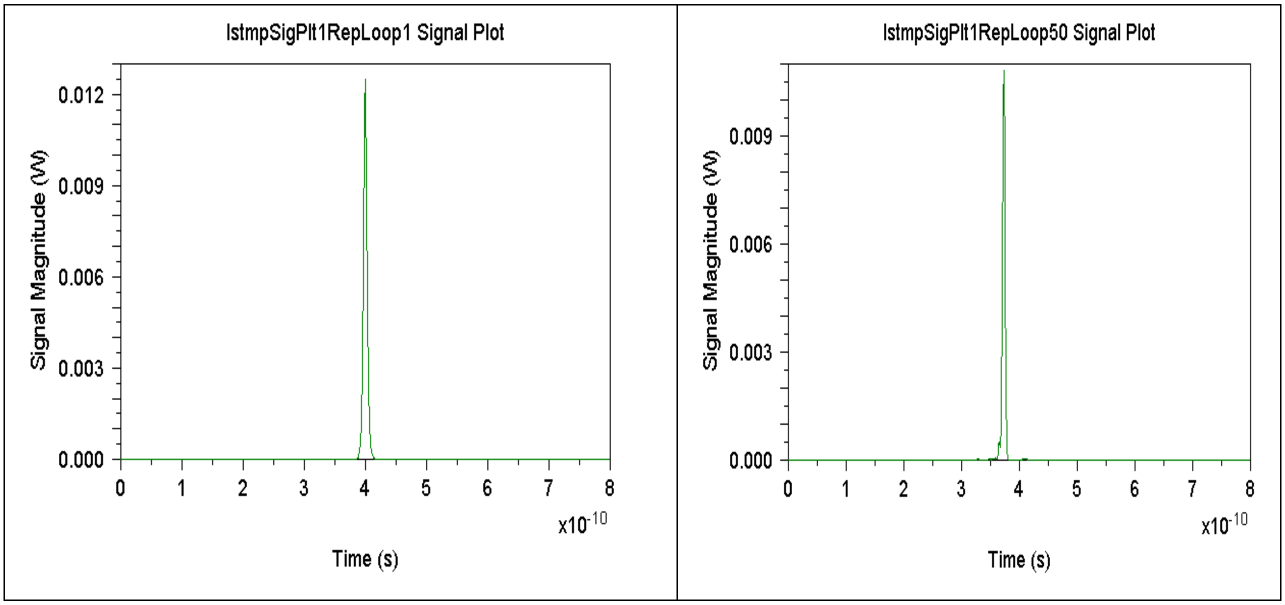


Figure 5.9 Eye diagram at receiver in dispersion managed fiber

The eye diagram for output signal at receiver is shown in figure 5.9. There is a very little distortion over 1000 km transmission. That demonstrates the robustness of path-averaged soliton pulse. The eye is wide open and provides error-free communication.



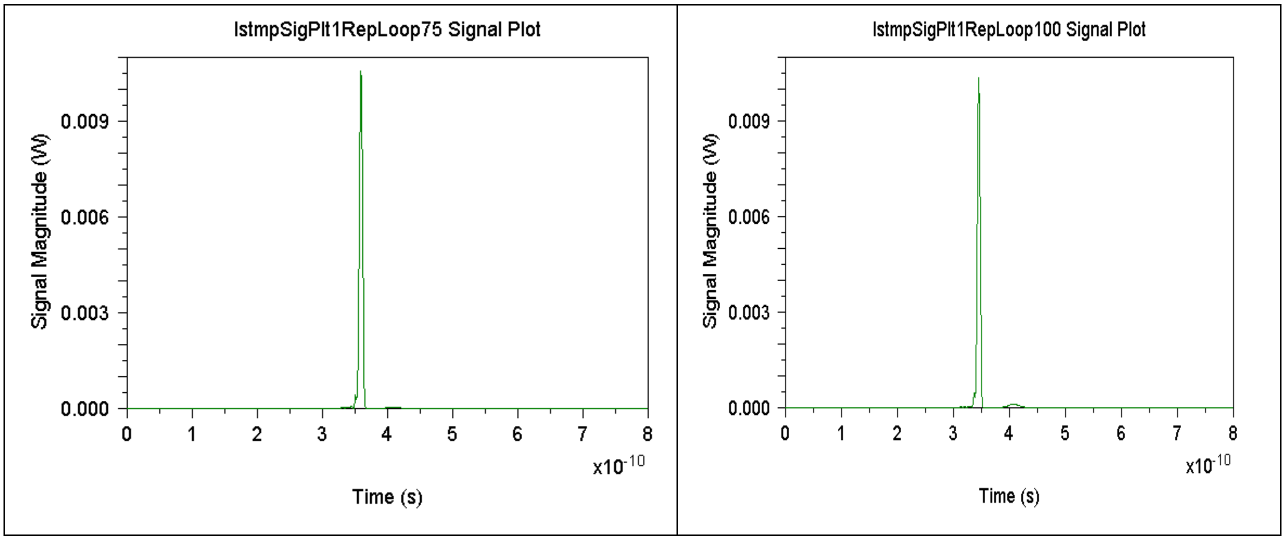


Figure 5.10 Signal plot at different loops

Figure 5.10 shows the signal magnitude Vs time plot at different loops. As the loops number increases, the distance increases. So, the magnitude of the pulse decreases.

5.5 CONCLUSION AND FUTURE SCOPE

The soliton transmission is very attractive as a potential method for realising high-speed, long-distance communication, but in soliton transmission, there are two serious problems. The first is related to the selection of fibers which have specified negative group velocity dispersion (GVD). This results in a low yield in terms of fiber fabrication. The second problem is that the amplifier spacing ***L,*** cannot be extended as far as that in conventional systems. In this paper, a new kind of soliton is studied that exist in a dispersion- allocated fiber system, and this enables the use of different kinds of fiber. The technique makes it possible not only to extend the repeater spacing, but also to reduce average GVD value. It is also possible to control the new solitons using filters, modulators, and optical gain. A fiber loss of 0.22 dB/km is achieved through 9000 Km with an amplifier spacing of 31 Km.

In this chapter, a dispersion managed soliton is presented. The soliton can be used for long distances up to 20,000 Km. Many other techniques can be invented to enhance the efficiency of the soliton transmission. The work can be extended to manage the nonlinear effects such as four-wave mixing (FWM) and cross-phase modulation (XPM) with dispersion. The transmission of different formats of data can also be interested area in research.

CHAPTER 6

CONCLUSION AND FUTURE PROSPECT

6.1 CONCLUSION

This chapter provides the summary of the research work done in this thesis. First the conclusion has been made from this study and then the suggestions for the future research are discussed. The major results obtained in this are summarized as follows:-

1. The systems for the optical transmission of microwave signals using intensity modulation direct detection technique have been analyzed. These systems offer the advantage of simplicity. However, large received optical power is necessary in order to overcome receiver thermal noise. In systems of length more than a few kilometers, the maximum source power is limited by the onset of nonlinear effects, especially SBS, in the optical fiber. In short systems, the limit is set by source and detector power handling limits. Optical pre-amplifiers enable near shot-noise-limited detection to be achieved even for low received powers. In particular, the availability of high-quality optical fiber amplifiers for the 1550 nm optical fiber transmission window makes it possible to realize high-quality IMDD transmission systems at that wavelength. It has been concluded that two system, single tone and multi tone can be recommended. From the eye diagrams, bit error rate (BER) and the Q-factor characteristics, it is clear that the single tone microwave system gives best performance at 5 GHz frequency for single tone system. By using multi tone various types of data can be transmitted at 5 GHz and 15 GHz frequency band. It is also analyzed that the output taken from EDFA is better than SOA. This is because EDFA amplifies all the frequencies simultaneously.
2. The development of high-capacity optical communication systems has required the import of microwave techniques in optical transmitters and receivers. Different results show that coherent system has better quality and is almost robust to fiber chromatic dispersion. Among the applications reviewed are wireless-over-fiber access systems, broadband signal distribution and access systems, and communications antenna remoting systems. A microwave over fiber communication system using coherent system (external modulator) is reported. Lorentzian laser is used with MZM to achieve a conversion of microwave band into baseband at which fiber operates. The coherent system realized in two forms, first, single tone and second, multi tone.

From the results, it is shown that like IMDD system, coherent systems are also give best performance at 5 GHz frequency for single tone system and 5 & 15 GHz for multi tone systems.

3. A new kind of soliton is studied that exist in a dispersion allocated fiber system, and this enables the use of different kinds of fiber. The technique makes it possible not only to extend the repeater spacing, but also to reduce average GVD value. Non-zero local dispersion helps to reduce FWM penalties. A pulse of 7 ps starts at initial value, then oscillating with amplitude going up to 3o ps, and after about 2,000 km the pulse width decreases and touches a value less than 3ps. After 4000 Km it converges to steady-state with pulse width changing periodically between 6 and 13 ps within each loop. It is also possible to control the new solitons using filters, modulators, and optical gain. A fiber loss of 0.22 dB/km is achieved through 9000 Km with an amplifier spacing of 31 Km.

6.2 FUTURE SCOPE

There is much scope for further work to improve component performance, particularly source output power, RIN, and modulation sensitivity; modulator insertion loss, power handling, and photo-detector power handling. The various parameters of microwave over fiber communication system using direct detection method can be modified using coherent system. The shot-noise limited receiver sensitivity is a major problem in detection of optical signal at receiver in direct detection. The direct detection systems are limited to intensity modulation (the use of angle modulation with interferometric detection at the receiver results in an intensity-modulated signal at the photodiode that has then to be detected conventionally and therefore does not yield SNR improvements) but there can be more types in modulation like frequency, or phase modulation. The soliton can be used for long distances up to 20,000 Km. Many other techniques can be invented to enhance the efficiency of the soliton transmission. The work can be extended to manage the nonlinear effects such as four-wave mixing (FWM) and cross-phase modulation (XPM) with dispersion. Till date the soliton propagation has not been commercially used and is yet to be practically realizable.

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