PERFORMANCE STUDY OF OPTICAL TRANSMISSION SYSTEM WITH FIBER NON-LINEARITIES

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Dedicated to

My Parents

APPROVAL

The thesis titled **"Performance Study Of Optical Transmission System With Fiber Non-Linearities"** submitted by Narottam Kumar Das, Roll no. 911350F, session 1989-90 to the Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and technology (B.U.E.T.) has been accepted as satisfactory for partial fulfillment of the requirements for the degree of Master of Science in Engineering (Electrical and Electronic).

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This work has been done by me and it has not been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

A theoretical analysis for optical wavelength division multiplexed transmission system is presented considering a single building block of an optical mesh network consisting of optical amplifiers, optical multiplexers and demultiplexers, splitters, fiber protection switch etc. Continuous phase frequency shift keying (CPFSK) modulation of the transmitting laser is considered with heterodyne delay-demodulation reception. The analysis is carried out to evaluate the degrading effect of fiber non-linearities, viz. chromatic dispersion and four-wave mixing (FWM) on the overall system performance. The expressions for the probability density functions for the random phase fluctuations due to above non-linear effects at the output of the IF filter are analytically formulated.

The bit error rate (BER) performance of the system is evaluated at a bit rate of 2.5 Gb/s for practical values of the receiver and system parameters and the optimum system parameters viz. optimum channel separation, maximum number of nodes for a mesh network, optimum input transmitter power etc are also determined for reliable system performance.

LIST OF FIGURES

LIST OF PRINCIPAL SYMBOLS

nm = Nano meter

dB = Decibel

μm = Micro meter

$e_s(t)$ = Output of the laser transmitter signal

P_s = Optical signal power

ω_s = Angular frequency of the optical carrier

ϕ_s = Angle modulation

$e_0(t)$ = Optical amplifier output signal

$e_{ASE}(t)$ = Optical amplifier's spontaneous emission

$e_{FWM}(t)$ = FWM output signal

P_{pqr} = FWM power generated within the fiber

f_{pqr} = FWM frequency

f_p = Carrier frequency of the p-th channel

f_q = Carrier frequency of the q-th channel

f_r = Carrier frequency of the r-th channel

E(t) = Total optical field at the output of the fiber

h(t) = Low-pass equivalent impulse response of the fiber

F^{-1} = Inverse Fourier transform

H(f) = Transfer function of the optical fiber span

D_c = Fiber chromatic dispersion factor

L = Fiber length / span

λ = Optical wavelength of the desired channel

C = Velocity of light

$E_{LO}(t)$ = Local oscillator signal

P_{LO} = Local oscillator power

f_{LO} = Local oscillator frequency

R_L = Receiver load resistance

K = Boltzmann's constant

T = Receiver temperature

B = Receiver bandwidth

n(t) = Total noise

$\phi_d(t)$ = Additive phase noise due to fiber chromatic dispersion

$\Psi(t)$ = Output phase

$n_0(t)$ = Filtered additive noise

σ^2 = Variance of total noise power

$\Theta_t(t)$ = Total phase noise

$\Delta\Psi_\tau$ = Accumulated phase over the demodulation interval

$\Delta\Psi_T$ = Total accumulated phase over the demodulation interval

h = Modulation index

τ = Delay time

* = Complex conjugate

K^2 = Correlation co-efficient

E[.] = Mathematical expectation

B_{eq} = Equivalent bandwidth

$I_0(.)$ = Zero-order modified Bessel function

pdf = Probability density function

$P(\Delta\Psi_T)$ = The pdf of $\Delta\Psi_T$

$\otimes$ = Convolution

$P_e|\Delta\Psi_T$= Error probability condition on $\Delta\Psi_T$

β = Linewidth of laser

$f_i(i=p,q,r)$= Optical frequency of the i-th channel

χ = Nonlinear susceptibility

A_{eff} = Effective core area

r = Modified radius

W = Modified diameter

α = Attenuation of fiber

l = Fiber length

L_{eff} = Effective fiber length

Δf = Frequency separation between two adjacent channels

B_e = Bandwidth of IF filter

B_0 = Bandwidth of optical amplifier

I_{sp} = Spontaneous emission current

I_{FWM} = Detector current due to FWM power

R_d = Responsivity of photodetector (A/W)

N_0 = Power spectral density of spontaneous emission

N_{sp} = Spontaneous emission factor

G = Gain of optical amplifier

h = Plank's constant

ν = Frequency of optical carrier

P_{sp} = Optical amplifiers spontaneous emission (ASE) power

I_{LO} = Detector current due to P_{LO}

I_s = Signal current due to P_{in}

N_{o-LOSP}= PSD of optical oscillator-ASE beat noise

N_{0-ssp} = PSD of optical signal-ASE beat noise

$G_{LO-PN}(f)$= Phase noise corrupted spectrum of LO signal

$G_{PN}(f-f_{IF})$= Phase noise corrupted spectrum of LO signal

$G_{FSK-PN}(f)$= Spectrum of phase noise corrupted FSK signal

N_{LO-FWM} = PSD of LO-FWM beat noise

N_{FWM} = PSD of FWM power

N_{S-FWM} = PSD of signal-FWM beat noise

P_{S-FWM} = Signal FWM beat noise power

P_{sp-sp} = ASE-ASE beat noise power

LIST OF ABBREVIATIONS

LASER = Light Amplification by Stimulated Emission of Radiation

LD = Laser Diode

LED = Light Emitting Diode

LO = Local Oscillator

PIN = Positive Intrinsic Negative

PD = Photodiode

APD = Avalanche Photodiode

th = Thermal

FWM-sp= FWM Spontaneous Emission

LO-sp = LO Spontaneous Emission

ssp = Signal Spontaneous Emission

LO-FWM= Local Oscillator FWM

s-FWM = Signal FWM

sp-sp = Spontaneous-Spontaneous

WDM = Wavelength Division Multiplexing

IM/DD = Intensity Modulation Direct Detection

FDM = Frequency Division Multiplexing

FCD = Fiber Chromatic Dispersion

FWM = Four-Wave Mixing

DFWM = Degenerate FWM

SBS = Stimulated Brillouin Scattering

SRS = Stimulated Raman Scattering

RIN = Relative Intensity Noise

SPM = Signal Phase Modulation

ASE = Amplifier's Spontaneous Emission

DFWM = Degenerate Four-Wave Mixing

OFCD = Optical Frequency Division Multiplexing

ASK = Amplitude Shift Keying

DPSK = Differential Phase Shift Keying

FSK = Frequency Shift Keying

CPFSK = Continuous Phase FSK

BER = Bit Error Rate

Km = Kilometer

MUX = Multiplexer

DMUX = Demultiplexer

W = Fiber Core Diameter

MWTN = Multiwavelength Transport Network.

CHAPTER - I

INTRODUCTION

1.1 Introduction and Historical Background of Fiber Optic Communication:

Since the early seventies, optical fibers have been seriously considered as a long range communication medium. Several fabrication techniques and specialized optical sources and detectors have been developed. Huge reductions in material attenuation have been obtained. It has been established that as compared to metal conductors / waveguides, size for size, optical fibers offer greater information capacity arising from a higher carrier frequency and lower material costs. Because of these reasons, during the last two decades there have been considerable advancements in the field of optical communication both in theory and practice [1]. The period 1965 to 1975 was devoted to the development of graded index systems operating at bit rates in the range of 8-140 Mbits and at wavelengths of 850-900 nm. However, the shortcomings of graded index fibers were soon apparent and by 1978 research had commenced on single mode fiber technology. This rapidly led to the establishment of 1300 nm single mode fiber design and system specifications for 140 Mbit/s operation. Recently, the scientists have started working at 1500 nm range for long haul systems and coherent detection systems [1-2].

Optical fiber communication technology has today permeated almost every field of modern society. In less than three decades, it has emerged from a mere theoretical concept to a commercial viability. Today, there is hardly any communication field where fiber optics has not left its mark. The need for and means of communication have always existed in human society. What we are observing today is a kind of communication revolution where information is created, managed, processed and distributed. This revolution is leading the society to an integrated global network that will carry the information in the form of video, data and voice channels across national boundaries, transferring the globe into a local network, overcoming time and distance and changing the overall concept of communication, business and ways of life.

The development of LASER in 1960 was a landmark for optical fiber communication using coherent light signal. Discovery of gas and solid state lasers gave impetus for fiber optic communication technology developments. Though these initial lasers had poor life times and were required to work at low temperature, today lasers have projected lifetimes of up to 10 years at room temperature and above. Accessibility of light emitting diodes (LED) to transfer an electrical signal into light energy, and PIN and avalanche photodiode (APD) to detect light signals and turn them back into electrical information have made fiber optic communication system simple and efficient [3].

1.2 Advantages of Optical Fiber Communication:

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

(a) Extra advantages of having low weight and small in size.

(b) The immunity to ambient electrical noise, ringing echoes or electromagnetic interference.

(c) No hazards of short circuits as in metal wires.

(d) No problems when used in explosive environments.

(e) Immunity to adverse temperature and moisture conditions.

(f) Lower cost of cables per unit length compared to that of metal counter-part.

(g) No need for additional equipment to protect against grounding and voltage problems.

(h) Very nominal shipping, handling and installation costs.

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

1.3 Detection Schemes:

In optical communication system, there are two important detection schemes employed, viz, the intensity modulation direct detection (IM/DD) and coherent detection [4-5]. In the direct detection scheme, the intensity of received optical field is directly converted to a current by a photodetector. The sensitivity of an ideal direct detection receiver is determined by the statistical distribution of the detected photons. At higher data rates the performance of the practical direct detection receiver deviates further from the quantum limited case since the electronic preamplifier usually has a rising noise versus frequency characteristic. Therefore, coherent detection will be beneficial for high capacity systems working at the longer wavelengths.

Coherent optical (light) detection is the optical analogy of superheterodyne radio detection. Thus a coherent light receiver first converts the incoming signal from the optical regime down to the radio regime and then uses conventional electronic circuity to perform various signal processing operations such as amplification and demodulation. This technique has been able to provide large increases in receiver sensitivity (>20 dB) compared to what one could get with direct detection systems using avalanche photodiodes [4]. This technique is quite suitable in the wavelength range of 1.3 to 1.6 μm and capable of providing the `quantum limit' of receiver sensitivity (10 photons/bit at 10^{-9} error rate). Since here the detection is shot noise limited rather than thermal noise limited, repeater spacing can be increased. It allows for the use of frequency and phase modulation of light. Also the generation of large number of closely spaced optical frequency division multiplexed (FDM) channels is possible [6].

The advantages of coherent detection system can be expressed in terms of improved receiver sensitivity. The performance of a coherent detection system is seriously affected by three important parameters, viz; (i) phase noise of transmitting and local oscillator laser (ii) extinction ratio of LD and (iii) the state of polarization of the received signal [4-7].

1.4 Limitations of Optical Fiber Communication Systems:

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

The important limit in optical communication is that the sensitivity of optical receiver is dictated by quantum effects. Other factors such as background light, dark current, post detection amplifier noise and transmitter imperfections also affect considerably the receiver sensitivity. The limits on channel are related to input coupling, loss and delay distortions.

Other limitations of optical transmission systems are due to the fiber chromatic dispersion (FCD), four-wave mixing (FWM) [7-16], Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS), phase noise of laser, Relative intensity noise (RIN), Signal phase modulation (SMP), Optical Amplifier's Spontaneous Emission (ASE), etc., [17-21].

Dispersion will play an increasing role on the overall system performance in future high-speed systems. Dispersion is an important characterization factor of optical fiber as it determines the distortion of the output signals launched into the fiber. These in effect modifies the actual information carrying capacity or bit rate of the optical fiber. The dispersion in optical fiber may arise due to various reasons and in practice three main factors have been analyzed [9,15] namely:-

(i) material dispersion,

(ii) waveguide dispersion and

(iii) differential group delay or intermodal (or simply modal) dispersion.

The effect of chromatic dispersion can be overcome to some extent by dispersion compensation device which is based on differential time delay for the upper and the lower side band of the modulated signal [19].

Four-wave mixing (FWM) phenomenon is one of the important limiting factors in multichannel transmission systems. Four-wave mixing (FWM) refers to the process in which three input optical waves interact in a medium and generate a fourth wave [7-16]. The combined interference and diffraction effect therefore corresponds to four wave mixing (FWM) in the language of non-linear optics. The process is called degenerate if the frequencies of the three incident waves and the generated wave are equal. Degenerate four-wave mixing (DFWM) is a simple method to achieve phase conjugation i.e., to generate a wave with a phase which is the complex conjugate of one of the incident waves. In optical fiber transmission lines with optical in-line amplifiers, the generated FWM light accumulates and seriously influences system performance [10-11,13]. Several studies have been reported on the influence of fiber four-wave mixing effect on multichannel systems [7-16]. FWM process, as well as Stimulated Brillouin Scattering (SBS) has the potential to influence significantly the operation of optical transmission systems using narrow-linewidth single frequency laser. In the coherent transmission systems employing frequency division multiplexing (FDM), it is necessary to determine the channel frequency separation at the operating wavelength of the system. FWM process depends on the channel frequency separation, fiber chromatic dispersion and the fiber length.

Dense wavelength division multiplexing (WDM) or optical frequency division multiplexing (FDM) techniques have been intensely studied for future lightwave communications systems, including subscriber and trunk transmission networks. The theoretical and experimental results of the effects of FWM in OFDM system were reported by Maeda et al [8]. The theoretical expression for FWM power was presented to demonstrate the dependence of FWM power on various system parameters and the experimental results were provided and the system performance degradation due to FWM crosstalk in a 16-channel coherent system were described.

Litchman [11] has reported the bit-rate distance product limitations due to fiber non-linearities viz. SBS, FWM and dispersion limits in multichannel coherent optical communication system.

The theoretical performance limitations due to fiber chromatic dispersion on coherent ASK and DPSK system was reported by Elrefaie et al [9]. The experimental results of chromatic dispersion limitations on direct detection FSK and DPSK system was also reported [15].

The effect of FWM on direct detection FSK and FDM system is reported by Toba et al [6] with some experimental demonstrations. The amount of crosstalk due to FWM is evaluated both theoretically and experimentally.

The traditional way of compensating for optical loss in lightwave communication systems has been the rather cumbersome procedure of regeneration. Regeneration includes photon-electron conversion, electrical amplification, retiming, pulse shaping and finally electron-photon conversion. In many applications, direct optical amplification of the light signal would be advantageous. Optical amplifiers can be used in any system that is loss limited: i.e., dispersion effects are a limiting factor. This is the case for most systems operating near the dispersion minimum at 1.3μm, and the coherent lightwave systems with local area networks (LAN), where the main losses are from branching and taps, are also loss limited and can benefit from simple optical amplifiers.

Er^{3+}-doped fiber amplifiers are essentially promising because of their inherent matching to fiber lines, high output power, and insensitive to interchannel crosstalk compared to semiconductor laser amplifier (SLA) [20]. To date, several works have been reported for multichannel amplification using fiber amplifiers, such as investigations on interchannel modulation and mutual signal-gain saturation as well as demonstrations of 16-channel common amplification [20-21]. They studied an Er^{3+}-doped fiber amplifier for multichannel systems, from the point of clarifying the ultimate capacity and the applicable number of channels.

Semiconductor laser amplifiers have been studied for a number of years. Significant work at 0.8-μm wavelength was done in the early 80's. Recently major progress has been made in long wavelength devices. Optical amplifiers with high gain, low gain ripple, low noise, and high saturation output power have been reported. Optical amplifier system applications have also been reported, both applications for preamplifiers and in-line amplifiers[20-21].

As optical amplifiers have advanced to the stage that actual system use might be possible in the near future, it is important to know the system consequences, its advantages and limitations. The theoretical as well as experimental investigations of optical amplifier lightwave systems are already reported [20-21]. Noise levels, bit-error-rate characteristics (BER), receiver sensitivities, and power penalties are calculated functions of the relevant optical amplifier parameters.

1.5 The objective of this Thesis:

The objectives of this thesis work are:

(1) To develop a nobel theoretical analysis for multiwavelength optical transmission system with CPFSK modulation and delay-demodulation heterodyne reception.

(2) To carry out the analysis to include the effect of fiber non-linear effects, viz. four-wave mixing (FWM), chromatic dispersion etc. in the presence of receiver noise and photodetector shot noise.

(3) To evaluate the system performance at a bit rate of 2.5 Gb/s and determine the optimum system parameters, viz. optimum fiber span, optimum number of nodes, optimum bandwidth and channel separation, maximum allowable transmitter power and maximum number of channels that can be transmitted for reliable system performance.

1.6 Brief Introduction to this Thesis:

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

In chapter 2, a nobel theoretical analysis for multiwavelength optical transmission system is presented which accounts for the nonlinear effects of optical fibers on the system performance in the presence of receiver noise and photodetector shot noise.

Chapter 3 provides the performance results of multiwavelength optical transmission system for different sets of values of receiver and system parameters at a bit rate of 2.5 Gb/s.

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

CHAPTER - II

PERFORMANCE ANALYSIS OF MULTIWAVELENGTH OPTICAL TRANSPORT NETWORK

2.1 Introduction:

Telecommunication networks of the future must be capable of adapting to rapid changes in the network traffic requirements. This is a consequence of the introduction of a new narrowband and broadband services with, at present, uncertain demands of bitrates, signal formats, etc.. Today, the development of telecommunication networks is constrained by the influencible interference between the optical high-speed fiber interconnection networks, and the electronic terminals at switch nodes. The vast bandwidth potential of the optical fiber cannot be exploited easily since the existing electronic interface is designed for specific multiplexing schemes and bitrates. Therefore, post installation changes will be required which is expensive. Optical technologies may be employed to provide the required capacity and flexibility. Until now, advanced optical techniques for time switching and frequency switching are still immatured compared to the electronic counterparts, whereas optical space switching and wavelength division multiplexing (WDM) [22] provide attractive solutions to some of the improved networking functions required.

The dimension of an optical network is limited by a number of effects, such as laser phase noise, Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS), Amplifier's Spontaneous Emission (ASE), laser saturation, reflection, jitter accumulation, signal bandwidth narrowing caused by filter concatenation and more prominently due to the fiber four-wave mixing (FWM). The effect of fiber four-wave mixing (FWM) depends on the number of wavelengths/channels transmitted, fiber chromatic dispersion, separation between two adjacent channel wavelengths, fiber span between two nodes, bandwidth of optical multi/demultiplexers etc.. Significant amount of research works have been carried out during the last few years to estimate the amount of FWM power and the crosstalk induced by FWM effect in multiwavelength optical networks [6,8, 10-15]. Crosstalk effects due to FWM in direct detection optical FSK multiwavelength optical transmission system is already reported [6]. A theoretical model of an optical network incorporating wavelength selective elements, amplifiers, couplers and switches is also reported where IM/DD technique is considered [23] and the network dimensions have been shown to be limited by the optical crosstalk in the switch matrices, the FWM effects and the polarization dependent loss in optical components. Although, the FWM power in a coherent multiwavelength transport network is experimentally reported [10-15], no theoretical analysis is yet reported which accounts for the above mentioned system imperfections on coherent multiwavelength optical transport network.

In this chapter, a nobel theoretical analysis is provided for wavelength division multiplexed (WDM) coherent optical transmission system considering a single network element or a building block for an optical mesh network. The analysis is carried out to evaluate the impact of fiber non-linear effects, viz. chromatic dispersion and fiber four-wave mixing on the overall system performance. Theoretical results based on the analysis is provided in the next chapter.

2.2 System Architecture:

A schematic architecture for the optical core network is shown in Fig. 2.1. The optical nodes are linked in a mesh configuration where transmission in opposite directions in the network is carried over two separate sub-networks. Optical isolators are assumed to eliminate problems caused by optical reflections. An optical path through the network will typically comprise a number of fiber transmission sections interconnected by optical network nodes incorporating optical space switches, optical amplifiers and WDM components. This network forms a high capacity optical transport layer of simple functionality with access to an electronic transport layer of limited bandwidth capable of providing a number of network management functions, drop-insert of new channels, etc.. Each module in the optical network consists of a network node and a length of fiber. If operation of the single network elements is independent of the overall network architecture, this approach allows simple overall network configuration and ease of upgrade and extensions.

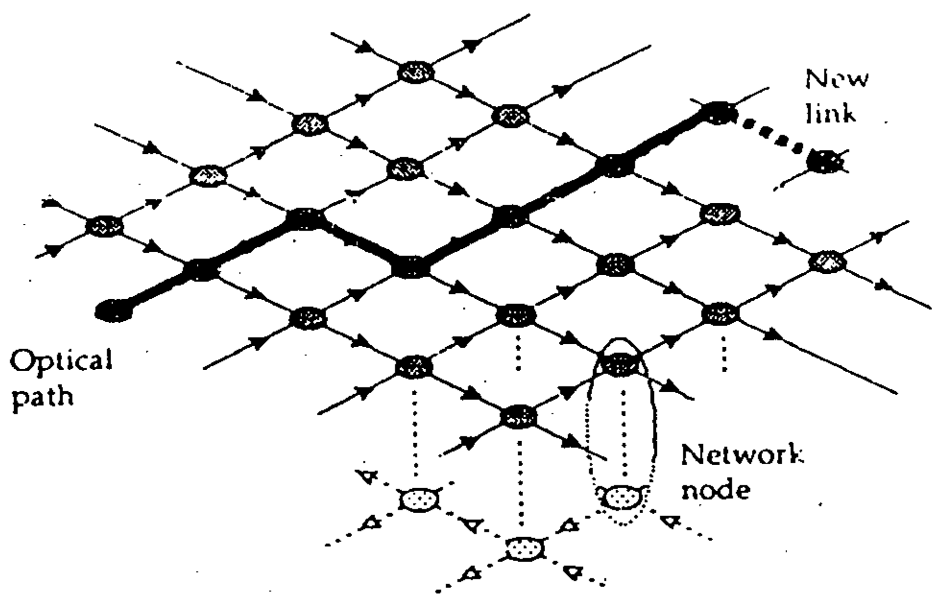

Fig.2.1 Optical mesh network.

In Fig. 2.2 a single network module (building block) is illustrated along with a schematic of an optical path through the network. An optical building block comprises wavelength selective elements for improved capacity and flexibility, amplifiers for signal level restoration, a splitter and a small switch for path protection, an optical crosspoint switch matrix, and a length of fiber for network node interconnection. The signals at the input and at the output of a network building block are to maintained at the same level.

2.3 Transmitter and Receiver Models:

The transmitter and receiver models considered in the analysis is shown in Fig. 2.3. For each channel we consider CPFSK modulation of the transmitter DFB laser using direct frequency modulation of its driving current as shown in Fig.2.3(a).

In the receiver we consider heterodyne delay-demodulation reception. The model of the optical heterodyne delay-modulation receiver is shown in figure 2.3(b). The light source used by the transmitter is assumed to be a single-mode laser, and the receiver includes a similar laser as a local oscillator (LO). The received optical signal is mixed with the LO signal. The combined optical signal is detected by a PIN photodetector and thus a microwave intermediate frequency (IF) electrical signal is produced. During the conversion process, Gaussian noise is added in three ways, (i) shot noise produced in the process of

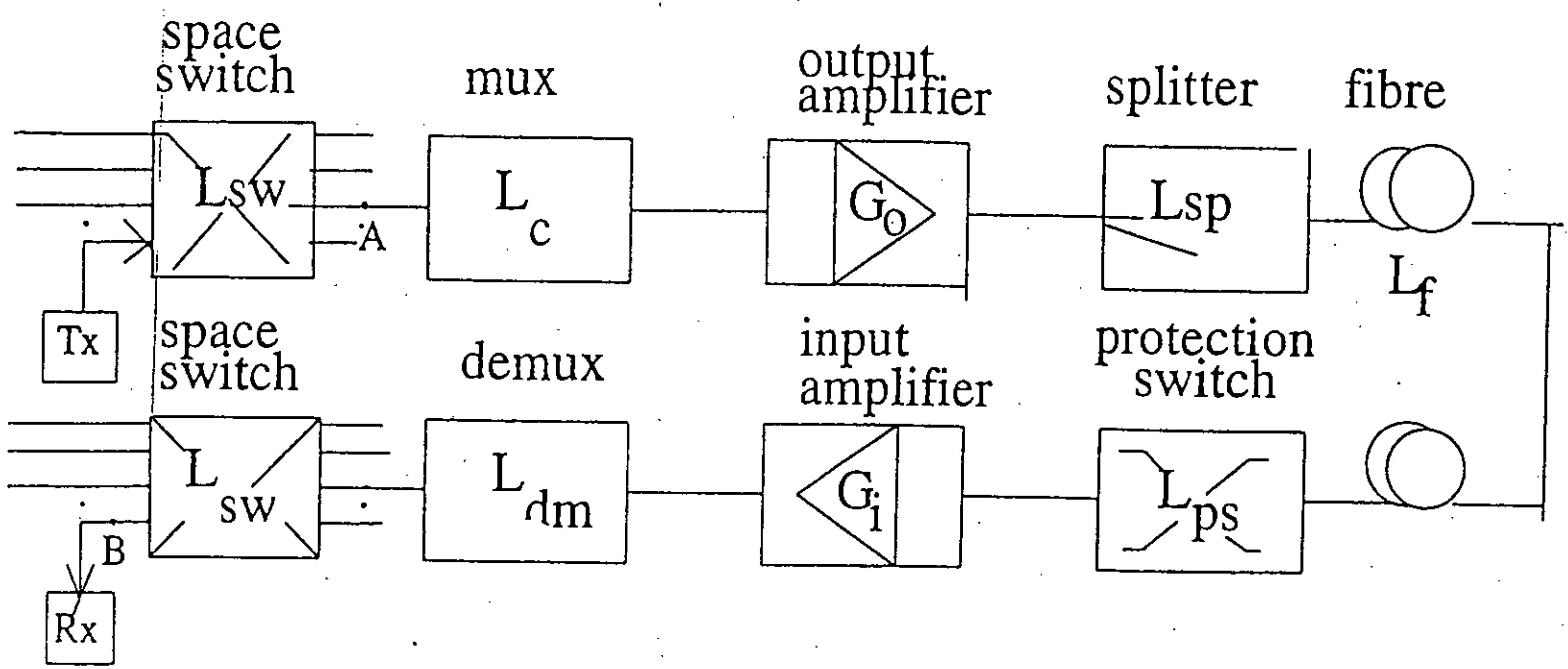

Fig.2.2 Schematic of optical path between two consecutive nodes.

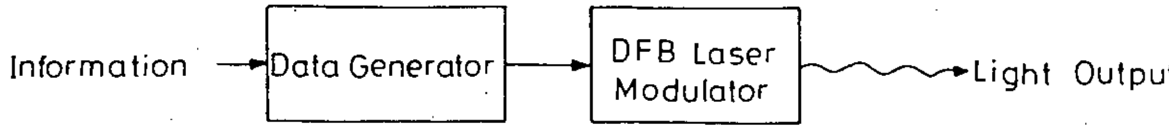

Fig.2.3a Block diagram of an optical transmitter.

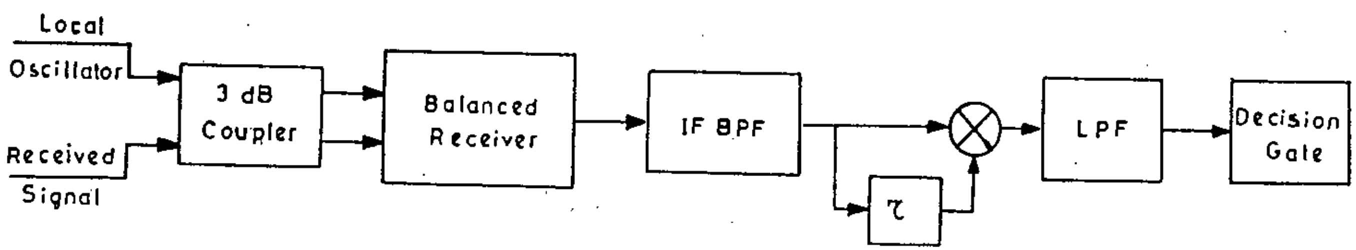

Fig.2.3b Schematic diagram of a typical CPFSK-DD optical heterodyne receiver.

photodetection, (ii) thermal noise introduced by the circuitry following the photodetector, and (iii) beat noise terms arising out from the beating of the signal, local oscillator power, FWM signal and optical amplifier's spontaneous emission (ASE) noise in the photodetection process.

The IF signal at the output of photodetector is filtered by a bandpass IF filter centered at the IF frequency. In the absence of laser phase noise and with ideal LD FM response, the optical IF filter would be a matched filter with integration time equal to bit period. With phase noise present, a shorter integration time and hence, a larger IF bandwidth ($B_{IF}>1/T$) is required in situation experiencing non-zero IF linewidth and / or nonflat LD FM response.

After IF filtering, demodulation is performed by delay-demodulation technique. The signal and its time-delayed (τ sec. delay) version are multiplied. With certain conditions maintained, the polarity of the output signal, after passing through a low pass filter, contains the bit information. Data decision is made by using the polarity of this output signal.

2.4 Theoretical Analysis of Coherent Optical Multiwavelength Transmission System:

2.4.1 The Optical Signal:

The optical signal at the output of the laser transmitter can be expressed as

$$e_s(t) = \sqrt{2P_s}\, e^{j[\omega_s t + \phi_s(t) + \theta_{tr}(t)]} \tag{2.1}$$

where P_s is the optical signal power

ω_s is the angular frequency of the optical carrier

θ_{tr} represents the phase noise of transmitting laser

and ϕ_s represents the angle modulation given by

$$\phi_s = 2\pi f_d \cdot \int_{-\infty}^{t} \sum_{k=-\infty}^{\infty} a_k . P(t-kT)\, dt \tag{2.2}$$

where P(t) is the phase shape, a_k is the k-th information bit, f_d is the peak frequency deviation and T is the bit period.

At the optical amplifier output, the signal is given by

$$e_o(t) = \sqrt{2GP_s}\, e^{j[\omega_s t + \phi_s(t) + \theta_{tr}(t)]} + e_{ASE}(t) \tag{2.3}$$

where G is the amplifier gain and

$e_{ASE}(t)$ is the optical amplifier's spontaneous emission signal which is given by [20]

$$e_{ASE}(t) = \sum_{K=-M}^{M} \sqrt{2N_0\delta v}\; e^{j[\omega_s t + 2\pi k\delta v t + \Omega_k]} \tag{2.4}$$

where $N_0 = N_{sp}\ (G - 1)\ hv$ is the power spectral density of ASE signal, N_{sp} is the spontaneous emission factor, hv is the photon energy, δv is the frequency separation between the discrete components of $e_{ASE}(t)$. Such that M becomes as integer $M = B_0/2\delta v$, B_0 is the bandwidth of optical amplifier and Ω_k is the random phase for each component of the spontaneous emission [20].

If the Four-wave mixing (FWM) power generated within the fiber, which falls on the desired signal channel frequency, is represented by P_{pqr} with frequency f_{pqr}, then the FWM signal is given by [8,10,13]

$$e_{FWM}(t) = \sum \sqrt{2P_{pqr}} \exp[j2\pi f_{pqr} t + \theta_{pqr}] \tag{2.5}$$

where, $f_{pqr} = f_p + f_q - f_r$, Θ_{pqr} is the random phase of FWM signal and f_p, f_q and f_r represents the carrier frequency of the p-th, q-th, and r-th channel respectively. The expression for P_{pqr} is given in Appendix A.

The total optical field at the output of the fiber is given by

$$\begin{aligned} E(t) &= e_s(t) \otimes h(t) + e_{FWM}(t) + e_{ASE}(t) \\ &= \sqrt{2P_s}\, \exp[j2\pi f_s t + \phi_s{}'(t)] + e_{FWM}(t) + e_{ASE}(t) \end{aligned} \tag{2.6}$$

where $\otimes$ denotes convolution, h(t) is the low-pass equivalent impulse response of the fiber and

$$\phi_s'(t) = \phi_s(t) \otimes h(t)$$

$$h(t) = F^{-1}[H(f)]$$

where F^{-1} denotes inverse Fourier transform and H(f) is the transfer function of the optical fiber span and is given by filter [9]

$$H(f) = e^{-j\alpha f^2} \tag{2.7}$$

where $\alpha=\pi D_c L\lambda^2/C$, D_c is the fiber chromatic dispersion factor, L is the fiber length, λ is the optical wavelength of the desired channel and c is the velocity of light.

Now $\phi_s'(t)$ can be expressed as [24]

$$\begin{aligned} \Phi_s'(t) &= 2\pi f_d \cdot \int_{-\infty}^{t} \sum_{k=-\infty}^{\infty} a_k P(t-kT) \otimes h(t)\, dt \\ &= 2\pi f_d \cdot \int_{-\infty}^{t} \sum_{k=-\infty}^{\infty} a_k p'(t-kT)\, dt \end{aligned} \tag{2.8}$$

where $p'(t) = p(t) \otimes h(t)$

The Local oscillator (LO) signal, with power P_{LO} and frequency f_{LO}, is given by

$$E_{LO}(t) = \sqrt{2P_{LO}}\, \exp[j2\pi f_{LO}t + \theta_{LO}] \tag{2.9}$$

Following Appendix B, the IF signal r(t) can be written as

$$r(t) = ACos[\omega_{IF}t + \phi_s^{/}(t) + \phi_{FWM} + \theta_t(t)] + n(t) \tag{2.10}$$

where R_L is the receiver load resistance, K is the Boltzmann's constant, T is the receiver temperature in ^0K and B is the receiver bandwidth, $\theta_t(t)$ is the composite phase noise of transmitting and LO laser, and n(t) is the total noise and ϕ_{FWM} and A are given by

$$\phi_{FWM} = \tan^{-1}\frac{\sqrt{P_{FWM}P_{Lo}}Sin\theta_{pqr}}{\sqrt{P_sP_{Lo}}+\sqrt{P_{FWM}P_{Lo}}Cos\theta_{pqr}} \tag{2.11}$$

$$A = 2R_d\sqrt{(\sqrt{P_sP_{Lo}} + \sqrt{2P_{FWM}P_{Lo}}Cos\theta_{pqr})^2 + (\sqrt{2P_{FWM}P_{Lo}}Sin\theta_{pqr})^2} \tag{2.12}$$

2.4.2 Output Phase of IF Filter:

The IF signal at the output of P.D. (input to IF filter) is

$$r(t) = ACos[2\pi f_{IF}t + \phi(t)] + n(t) \tag{2.13}$$

where

$$\phi(t) = \phi_{FWM}(t) + \phi_s^{/}(t) + \theta_t(t)$$

and

$$\phi_s^{/}(t) = \pm 2\pi f_d t + \phi_d(t) \tag{2.14}$$

$$\phi_d(t) = 2\pi f_d.\int_{-\infty}^{t}\sum_{k\neq 0} a_k p^{/}(t - KT)\,dt \tag{2.15}$$

where $\phi_d(t)$ represents the additive phase noise due to fiber chromatic dispersion.

We assume the IF filter to be a bandpass filter centered about f_{IF} with bandwidth 2B, where B is the bandwidth of the transmitted signal. The above equation is a realistic value for practical values of laser linewidths BT=2 is good for a practical choice [5,25].

The output of the IF filter can be written as,

$$
\begin{aligned}
y(t) &= r(t) \otimes q(t) + n_o(t) \\
&= \int_t^{\infty} q(t)\; r(t - t')\, dt' + n_o(t) \qquad (2.16) \\
&= A(t)\, Cos[2\pi f_{IF} t + \psi(t)] + n_o(t)
\end{aligned}
$$

where $\Psi(t)$ is the output phase and $n_0(t)$ is the filtered additive noise with variance σ^2, $q(t) = F^{-1}[Q(f)]$ is the impulse response of IF filter.

The IF signal-to-noise ratio (IF SNR) can be defined as

$$
IF\ SNR = \frac{A^2}{2\sigma^2} \qquad (2.17)
$$

where σ^2 is the variance of total noise n(t).

The total noise power σ^2 is given by

$$\sigma^2 = P_{shot} + P_{th} + P_{FWM\text{-}sp} + P_{LO\text{-}sp} + P_{ssp} + P_{LO\text{-}FWM} + P_{s\text{-}FWM} + P_{sp\text{-}sp} \quad (2.18)$$

where $P_{FWM\text{-}sp}$, represents the FWM-spontaneous emission beat noise power, $P_{LO\text{-}sp}$ is the local-oscillator-spontaneous emission beat noise power, P_{ssp} is the power of signal-spontaneous emission beat noise, $P_{LO\text{-}FWM}$ is the local-oscillator-FWM beat noise power, $P_{s\text{-}FWM}$ is the signal-FWM beat noise power and $P_{sp\text{-}sp}$ is the spontaneous-spontaneous beat noise power. The expressions for these above noise powers are given in Appendix C.

Defining the normalized equivalent baseband filter impulse response as

$$h_{IF}(t) = \frac{q(t)}{Q(f_{IF})} \cdot e^{-j2\pi f_{IF} t} \quad (2.19)$$

where, $h_{IF}(t)$ is complex if $Q(f)$ is not symmetrical around f_{IF} i.e., if the IF filter is not symmetric.

According to Bedrosian and Rice [24] showed that the output phase process can be written as

$$\psi(t) = Re[h_{IF}(t) \otimes \phi'(t)] + \sum_{n=2}^{\infty} \frac{1}{n!} I_m[j^n f_n] \quad (2.20)$$

In the above equation (2.20) the first term represents linear filtering of the input phase $\phi'(t)$ and the summation represents various orders of distortion introduced by the filter. Assuming that the linear filtering term dominates, we get the output phase process relative to the carrier phase of the IF filter output, as

$$
\begin{aligned}
\psi(t) &= h_{IF}(t) \otimes \phi'(t) \\
&= h_{IF}(t) \otimes \phi(t) + h_{IF}(t) \otimes \theta_t(t) \\
&= h_{IF}(t) \otimes \phi_d(t) + h_{IF}(t) \otimes \phi_{FWM}(t) + h_{IF}(t) \otimes \theta_t(t) \\
&= h_{IF}(t) \otimes 2\pi f_d \int_{-\infty}^{t} \sum_{k=-\infty}^{\infty} a_k . p'(t - kT)\, dt \\
&+ h_{IF}(t) \otimes \phi_{FWM}(t) + h_{IF}(t) \otimes \theta_t(t) \\
&= 2\pi f_d . \int_{-\infty}^{t} \sum_{k=-\infty}^{\infty} a_k . g(t - kT)\, dt + \alpha_{FWM}(t) \\
&+ \theta_n(t)
\end{aligned}
\tag{2.21}
$$

Where $\otimes$ denotes convolution and

$$g(t-kT) = h_{IF}(t) \otimes P'(t - kT) \tag{2.21a}$$

$$\alpha_{FWM}(t) = h_{IF}(t) \otimes \phi_{FWM}(t) \tag{2.21b}$$

$$\Theta_n(t) = h_{IF}(t) \otimes \Theta_t(t) \tag{2.21c}$$

$$\Theta_t(t) = \Theta_{tr}(t) + \Theta_{LO}(t) \tag{2.21d}$$

Now, the accumulated phase over the demodulation interval with respect to IF carrier phase ($2\pi f_{IF}\tau$)

$$
\begin{aligned}
\Delta\psi_\tau &= \psi(t) - \psi(t - \tau) \\
&= 2\pi f_d . \int_{t-\tau}^{t} \sum_{k=\infty}^{\infty} a_k . g(t-kT)\, dt \\
&+ \alpha_{FWM}(t) - \alpha_{FWM}(t-\tau) \\
&+ \theta_n(t) - \theta_n(t-\tau)
\end{aligned}
\tag{2.22}
$$

The total accumulated phase over the demodulation interval can be written as in the following way, we have

$$\Delta\psi_T = 2\pi f_{IF}\tau + \Delta\psi_\tau$$

$$= 2\pi f_{IF}\tau - 2\pi f_d\tau \tag{2.23}$$

$$+ 2\pi f_d\tau + \Delta\psi_\tau$$

Hence putting the value of $\Delta\psi_\tau$ from equation (2.22), we have

$$\Delta\psi_T = [2\pi f_{IF}\tau - 2\pi f_d\tau]$$

$$+ [2\pi f_d\tau + 2\pi \int_{t-\tau}^{t} f_d \sum_{k=-\infty}^{\infty} a_k . g(t-kT)\, dt] \tag{2.24}$$

$$+ [\alpha_{FWM}(t) - \alpha_{FWM}(t-\tau)] + [\theta_n(t) - \theta_n(t-\tau)]$$

The IF center frequency is adjusted such that

$2\pi f_{IF}\tau = (m + 1/2)\pi$, m = 1, 2,.............. (2.25)

Then, we get from the equation (2.25)

$$\Delta\Psi_T = [(m + \frac{1}{2})\pi - \frac{\pi}{2}]$$

$$+ [2\pi f_d\tau + 2\pi \int_{t-\tau}^{t} f_d \sum_{k=-\infty}^{\infty}{}' a_k . g(t - kT)\, dt] \tag{2.26}$$

$$+ [\alpha_{FWM}(t) - \alpha_{FWM}(t - \tau)]$$

$$+ [\theta_n(t) - \theta_n(t - \tau)]$$

where $2\pi f_d\tau = \pi/2$, when modulation index satisfy the relation $h = T/2\tau$;

In the above equation (2.26).

(i) The first term represents the correct phase difference in an ideal case for desired frequency deviation when the transmitted bit is `1'.

(ii) The second term represents the phase distortion due to the effect of chromatic dispersion.

(iii) The third term represents the phase distortion due to FWM (four-wave mixing) phase noise.

(iv) The fourth or last term represents the phase distortion due to laser phase noise.

It is reported in Ref. [25] that noise correlation will be nonzero in a narrow deviation CPFSK-DD coherent optical receiver, and in particular, when using IF filters with a sharp cut-off and narrow bandwidth (tight-IF frequency), sensitivity penalties in excess of 0.5 dB have been demonstrated [25,26].

Because tight IF filtering will be an important requirement in dense optical WDM/FDM networks, we consider noise correlation at the filter output in presence of laser phase noise.

2.4.3 Data Decision:

Data Decision can be made using the polarity of the output signal $v_0(t)$. The polarity depends on the phase of the signal $v_0(t)$. When '1' is transmitted, the correct phase would be $(m + 1/2)\pi - \pi/2$, $m = 1, 2, \ldots\ldots\ldots\ldots$ So, an error will occur if $-\pi < \Delta\psi T_{\mathrm{mod}\ 2\pi} < 0$. Similarly, an error will occur when '0' is transmitted if $0 < \Delta\psi T_{\mathrm{mod}\ 2\pi} < \pi$. That means, error will occur when $0 < |\Delta\Psi T_{\mathrm{mod}\ 2\pi}| < \pi$.

Now, rewriting the equation (2.26), the total accumulated phase is

$$
\begin{aligned}
\Delta\psi_T = {} & [(m + \tfrac{1}{2})\pi - \tfrac{\pi}{2}] \\
& + [2\pi f_d \tau + 2\pi a_o \int_{t-\tau}^{t} f_d . g(t)\, dt \\
& + 2\pi \int_{t-\tau}^{t} f_d \sum_{k=-\infty}^{\infty} a_k . g(t - kT)\, dt] \qquad (2.27) \\
& + [\alpha_{FWM}(t) - \alpha_{FWM}(t - \tau)] \\
& + [\theta_n(t) - \theta_n(t - \tau)] \\
= {} & (m + \tfrac{1}{2})\pi + \phi_o + \Delta\phi_d + \Delta\alpha_{FWM} + \Delta\theta_n \\
= {} & \psi_o + \Delta\psi
\end{aligned}
$$

where Σ' excludes k = 0. It is to be noted that the desired phase change over the demodulation period is distributed by the effect of fiber chromatic dispersion, laser phase noise and the phase noise due to FWM power.

At the decision moment t_n, the current waveform at the output of the LPF can be expressed as

$$y_0(t) = \tfrac{1}{2}\,\mathrm{Re}[z_1^* z_2] \qquad (2.28)$$

where * denotes complex conjugate, $z_1 = y(t_n)$, and $z_2 = -jy(t_n-\tau)$. Furthermore, the in-phase and quadrature components of the narrow-band Gaussian noise process $n_0(t)$ viz. $n_I(t)$, $n_Q(t)$, $n_I(t-\tau)$ and $n_Q(t-\tau)$, become Gaussian random variables with a correlation matrix [25].

$$R_n = \sigma^2 \begin{vmatrix} 1 & 0 & \rho & 0 \\ 0 & 1 & 0 & \rho \\ \rho & 0 & 1 & 0 \\ 0 & \rho & 0 & 1 \end{vmatrix} \qquad (2.29)$$

where

$$\rho = \frac{E[n_I n_{Id}]}{\sigma^2} = \frac{E[n_Q n_{Qd}]}{\sigma^2} \qquad (2.30)$$

$$K^2 = \frac{1+\rho}{1-\rho} \tag{2.31}$$

is the correlation co-efficient (which is determined using the Wiener-Khintchine relations), E[.] denotes mathematical expectation, and an IF filter with a symmetrical frequency response about w_{IF} has been assumed. For an ideal rectangular filter bandwidth B Hz, $\rho = Sa(\pi B\tau_d)$, where $Sa(x) = \sin(x)/x$. For a Butterworth filter of order n and 3-dB bandwidth B_{3dB}, it can be shown that [25]

$$\rho = \sin\left(\frac{\pi}{2n}\right)\sum_{k=1}^{n} \exp[-\eta \sin(\chi_k)]\, x\, \sin[\chi_k + \eta\cos(\chi_k)] \tag{2.32}$$

where $\eta = \pi B_{3dB}$, $\chi_k = (2k-1)\dfrac{\pi}{2n}$, and the equivalent noise bandwidth is related to the 3-dB bandwidth by [23]

$$B_{eq} = B_{3dB}\frac{\pi/2n}{\sin(\pi/2n)} \tag{2.33}$$

For Gaussian IF filter [25]

$$\rho = \exp[-\pi(B_{eq}\tau)^2] \tag{2.34}$$

where $B_{eq} = 1.064B_{3dB}$.

2.4.4 Probability of Bit Error:

Using equation (2.28), the probability of error (for a decision threshold set to zero), conditioned on the random phase drift $\Delta\Psi_T$ is

$$P(e|\Delta\psi_T) = Pr[Re[z_1{}^* z_2] > 0 \,|\Delta\psi_T] \tag{2.35}$$

The integral solution to (2.35) is a recognizable problem in classical communication theory and, following [27, pp. 314-329], the average probability of error can be expressed as

$$P(e) = \int_{-\infty}^{\infty} p(\Delta\psi_T)\, p(e|\Delta\psi_T)\, d\Delta\psi_T \tag{2.36}$$

$$p(e|\Delta\Psi_T) = \frac{1}{2}[1-Q(a,b)+Q(b,a)] \tag{2.37}$$

$$\begin{Bmatrix} a^2 \\ b^2 \end{Bmatrix} = \frac{(1+K^2)(a^2{}_n+a^2{}_{nd}) \pm 4a_n a_{nd} K\sin\Delta\psi_T + 2(1-k^2)\, a_n a_{nd} \cos\Delta\psi_T}{8\sigma^2(1+\rho^2)} \tag{2.38}$$

where $p(\Delta\Psi_T)$ is the pdf of the random phase drift $\Delta\Psi_T$, and where $a_n = a(t_n)$, $a_{nd} = a(t_n - \tau_d)$, and $Q(\cdot,\cdot)$ is the Marcum Q-function [27,28]

$$Q(a,b) \triangleq \int_b^{\infty} x \exp(-\frac{a^2+b^2}{2})\, I_0(ax)\, dx \tag{2.39}$$

where $I_0(.)$ is the zero-order modified Bessel function, and

$$Q(a,0)=1, \qquad Q(0,b)=\exp\left(-\frac{b^2}{2}\right) \tag{2.40}$$

The pdf of $\Delta\Psi_T$, $p(\Delta\Psi_T)$ can be obtained from $p(\Delta\Psi)$ with mean value of Ψ_0 where $p(\Delta\Psi)$ is given by

$$p(\Delta\psi) = p(\Delta\phi_d) \otimes p(\Delta\alpha_{FWM}) \otimes p(\Delta\theta_n) \tag{2.41}$$

where $\otimes$ denotes convolution and $p(\Delta\phi_d)$, $p(\Delta\alpha_{FWM})$ and $p(\Delta\theta_n)$ represents the pdf of $\Delta\phi_d$, $\Delta\alpha_{FWM}$ and $\Delta\theta_n$ respectively. Following the Ref. [29], the pdf of $\Delta\alpha_{FWM}$ can be given by

$$p(\Delta\alpha_{FWM}) = \frac{e^{-u}}{4\pi}\int_0^{\pi} d\theta\, \sin\theta\,[1 + U + U\sin\theta\,\cos\Delta\alpha_{FWM}] \tag{2.42}$$
$$x\; e^{u\sin\theta\cos\Delta\alpha_{FWM}}, \qquad |\Delta\alpha_{FWM}| \le \pi$$

where

$$U = \frac{P_s}{\sum P_{pqr}} \tag{2.43}$$

The characteristic function $F_{\Delta\phi_d}(j\omega)$ $[F\{p(\Delta\phi_d)\}]$ of random variable $\Delta\phi_d$ can be shown to be [30]

$$\begin{aligned} F_{\Delta\phi_d}(j\omega) &= \prod_{i=1}^{\infty} \cos[\omega g_i(t')] \\ &= \sum_{i=1}^{\infty} \frac{(j\omega)^{2i}}{(2i)!} M_{2i} \end{aligned} \tag{2.44}$$

where $g_i(t') = |g(t' - iT)|$ and M_{2i} are the even order moments of the characteristic function of $\Delta\phi_d$ which can be evaluated using the following recursive relation [30]

$$M_{2i} = Y_{2r}(N)$$

$$Y_{2r}(i) = \sum_{j=0}^{r} \binom{2r}{2j} Y_{2j}(i-1)\, g_i^{2r-2j} \tag{2.45}$$

where N is the actual number of interfering terms in the summation of equation (2.44).

The pdf $p(\Delta\theta_n)$ has a zero-mean Gaussian distribution with variance $2\pi\Delta\nu\tau$ [24].

Since $\Delta\Psi_T$ is mod 2π, the equation (2.36) is to be written as

$$P(e) = \sum_{-\infty}^{\infty} \int_{-\pi}^{\pi} (P_e|\Delta\psi_T)\, P(\Delta\psi_T - 2n\pi)\, d\theta \tag{2.46}$$

This is the bit error rate (BER) expression for the coherent optical heterodyne CPFSK system with delay demodulation.

CHAPTER - III

RESULTS AND DISCUSSIONS

Following the theoretical analysis presented in chapter 2, the theoretical performance results for multiwavelength optical transport system is evaluated at a bit rate of 2.5 Gb/s with and without considering the FWM effect for several sets of values of the receiver and system parameters. The parameters used in the theoretical computations are:

Bit rate, B_r = 2.5 Gb/s

Fiber attenuation, α = 0.2 dB/Km

Fiber chromatic dispersion, D_c = 1 ps/nm-Km

Optical wavelength, λ = 1550 nm

Responsivity factor, R_d = 0.85

Local oscillator power, P_{lo} = 0.001 w (0 dBm)

Loss of WDM MUX, L_m = -4.0 dB

Loss of splitter, L_s = -3.0 dB

Loss of fiber protection switch, L_{ps} = -6.0 dB

Loss of WDM DMUX, L_{ldm} = -4.0 dB

Loss of cross-connect switch, L_{sw} = -10.0 dB

Gain of optical amplifier in the head-end, G_1 = 18.0 dB

Gain of optical amplifier in the fount-end, $G_2 = -G_1 - L_T$ (dB)

Bandwidth of optical filter, $B_{fp} = 4.0B_r$

Bandwidth of IF filter, $B_e = 0.7B_r$

Fiber core diameter, $W = 0.5 \times 11^{-6}$ m

Refractive index of fiber, n = 1.45

Nonlinear susceptibility, $\chi = 5 \times 10^{-14}$ m^3/watt-sec.

Thermal noise current spectral density, $I_{th} = 10^{-12}$ $A/\sqrt{Hz}$

The bit error rate (BER) performance results in absence of FWM effect for coherent CPFSK modulated MWTN with delay-demodulation is shown in Fig.3.1 as a function of the number of nodes M for three values of input transmitter power P_{in}= -10, -5, 0.0 dBm when fiber span L = 20 Km and number of WDM channels N = 11 and optical amplifier's bandwidth B_o = 15 GHz. The plots illustrate how the bit error rate varies with the number of nodes. It is found that for a given input power, the error rate increases with increasing value of the number of nodes due to accumulation of optical amplifier's spontaneous emission (ASE) from one node to another. At an specified BER, the allowable number of nodes is more at higher input power. For example, at BER = 10^{-9} the allowable number of nodes is around 30 when P_{in} = -10 dBm, when P_{in} is increased to 0 dBm, the number of allowable nodes reaches around 300.

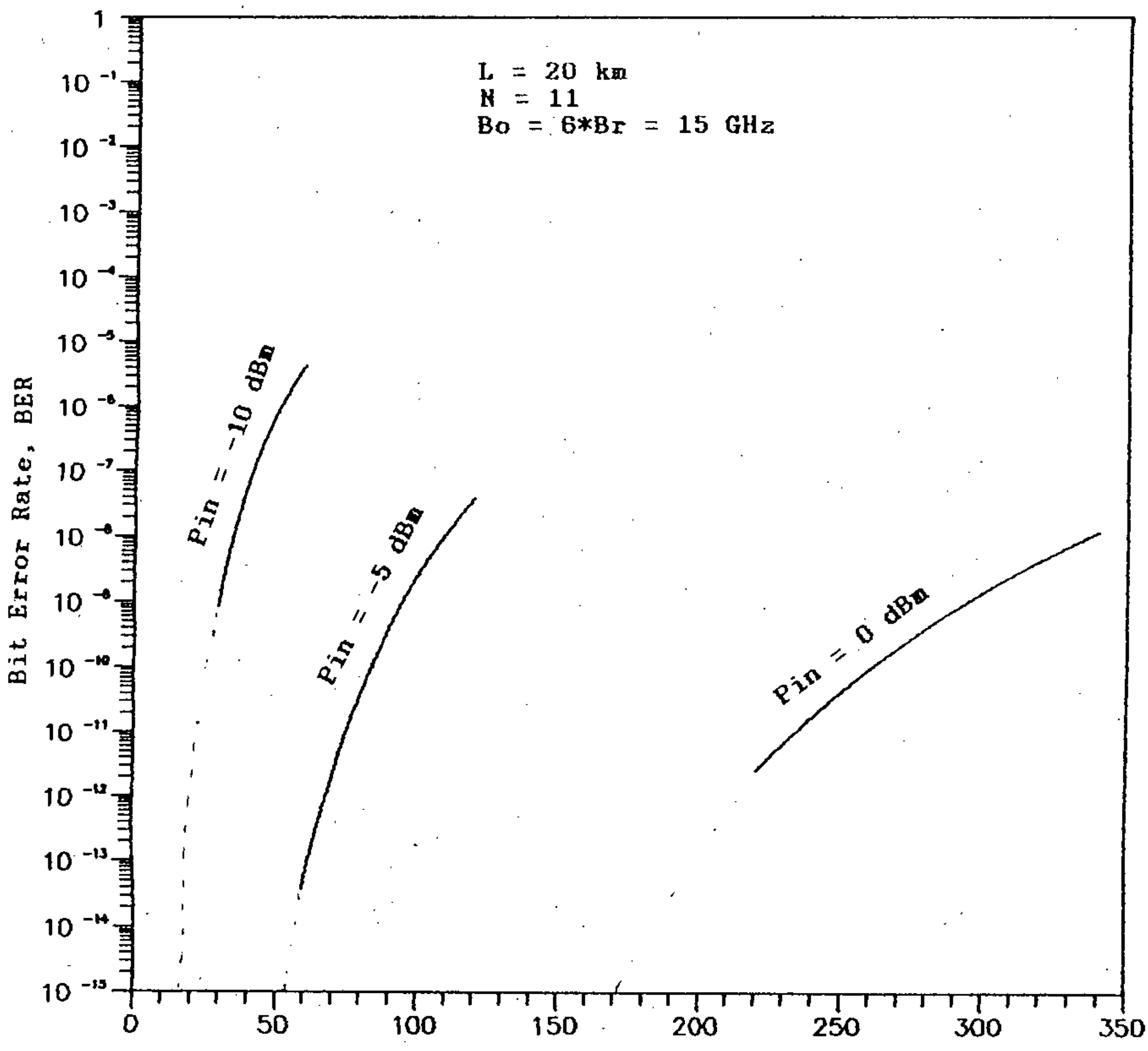

Fig.3.1 Bit error rate (BER) performance of optical multiwavelength transport network (MWTN) at a bit rate of 2.5 Gb/s as a function of the number of nodes M when number of channels N=11, fiber span L=20 Km, optical bandwidth B_o=6Br=15 GHz and P_{FWM}=0.0 for three different values of the optical transmitter power P_{in} (dBm).

When the fiber span is increased to 50 Km, the performance results are depicted in Fig.3.2. Comparing with Fig.3.1 it becomes evident that for the same input power the number of allowable nodes is reduced due to increased fiber span. When L is increased to 100 Km, the number of allowable nodes are further reduced as is evident from Fig.3.3. This is due to increased ASE with increased amplifier gain to meet the additional fiber loss due to increased fiber span.

When the optical amplifier's bandwidth B_o is increased to 10 times B_r i.e., 25 GHz, the performance results are shown in Fig.3.4 for fiber span L = 100 Km. Comparison of Fig.3.4 with Fig.3.3 reveals that increased optical bandwidth causes the system performance to be degraded and the allowable number of nodes is considerably reduced at BER = 10^{-9} at a given input power P_{in} (dBm). This is due to increased ASE and several beat noise terms arising out of beating of ASE with signal and local oscillator signals at increased optical bandwidth. The number of node is further reduced as the optical bandwidth is further increased to B_o = 50 GHz as depicted in Fig.3.5. For example, P_{in} = 0 dBm, the number of allowable nodes at BER = 10^{-9} is around 9 when B_o = 50 GHz and it is approximately 17 when B_o = 25 GHz.

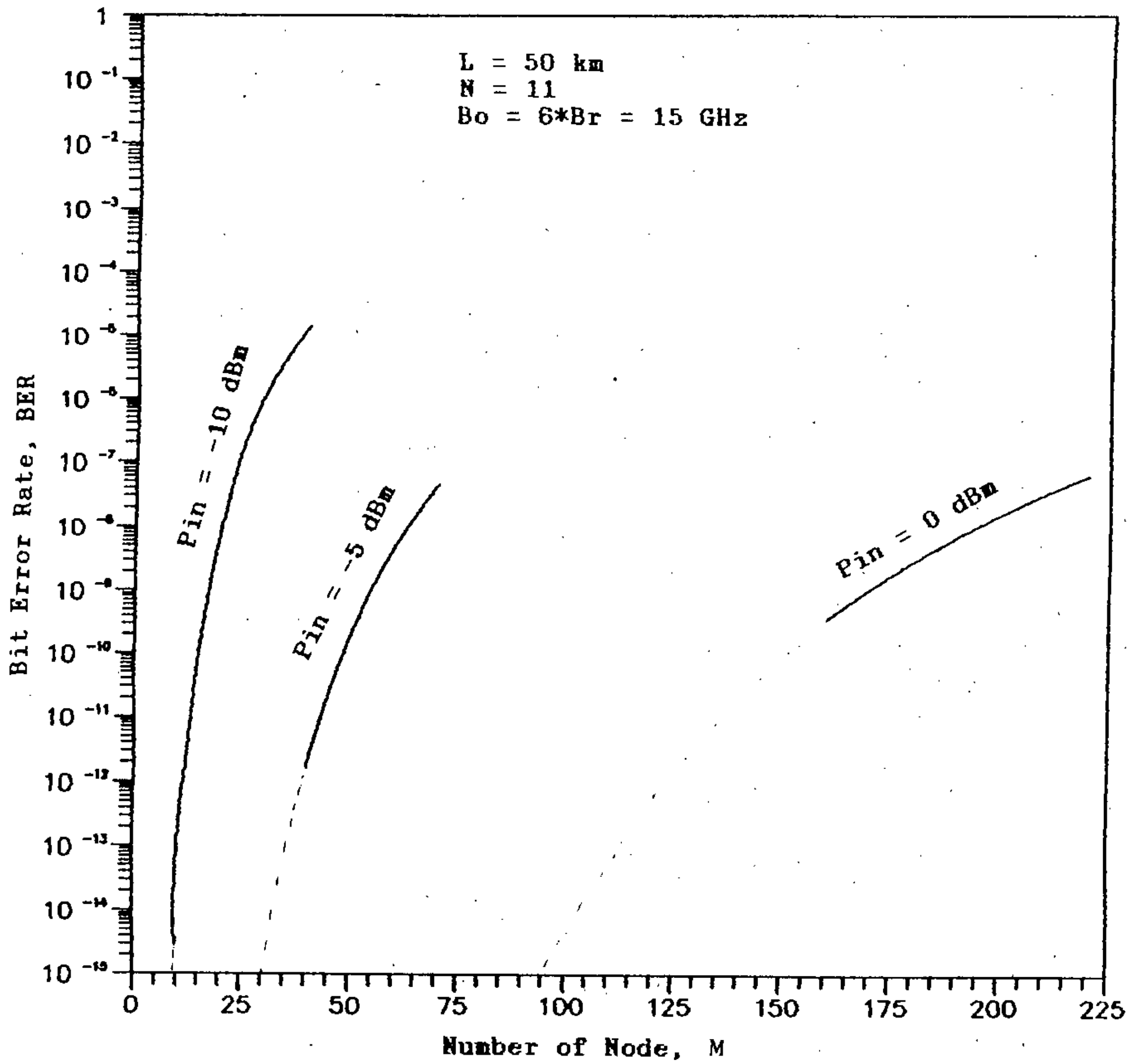

Fig.3.2 Bit error rate (BER) performance of optical MWTN at a bit rate of 2.5 Gb/s as a function of the number of nodes M when number of channels N=11, fiber span L=50 Km, optical bandwidth B_o=6Br=15 GHz and P_{FWM}=0.0 for three different values of the optical transmitter power P_{in} (dBm).

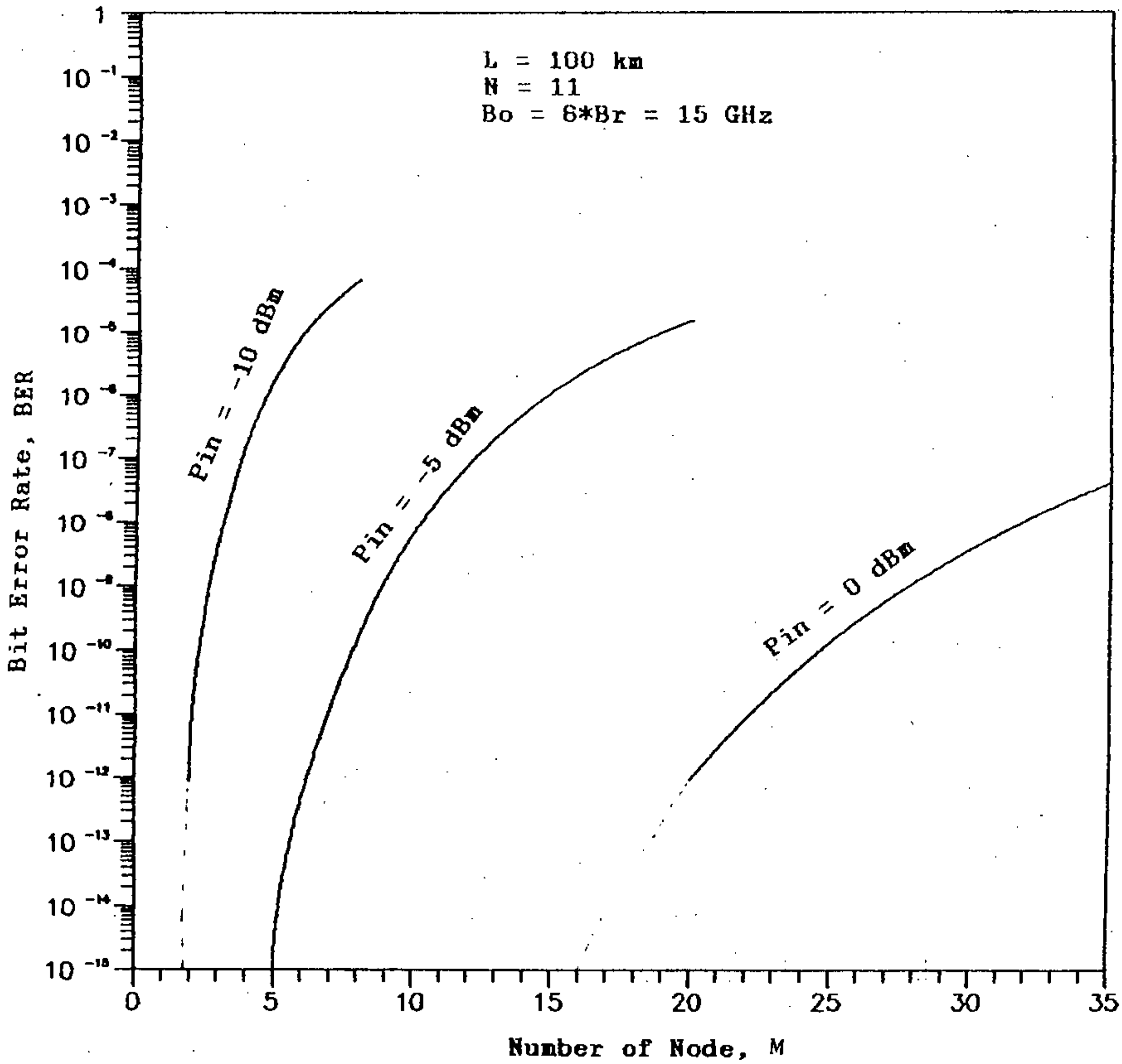

Fig.3.3 Bit error rate (BER) performance of optical MWTN at a bit rate of 2.5 Gb/s as a function of the number of nodes M when number of channels N=11, fiber span L=100 Km, optical bandwidth B_o=6Br=15 GHz and P_{FWM}=0.0 for three different values of the optical transmitter power P_{in} (dBm).

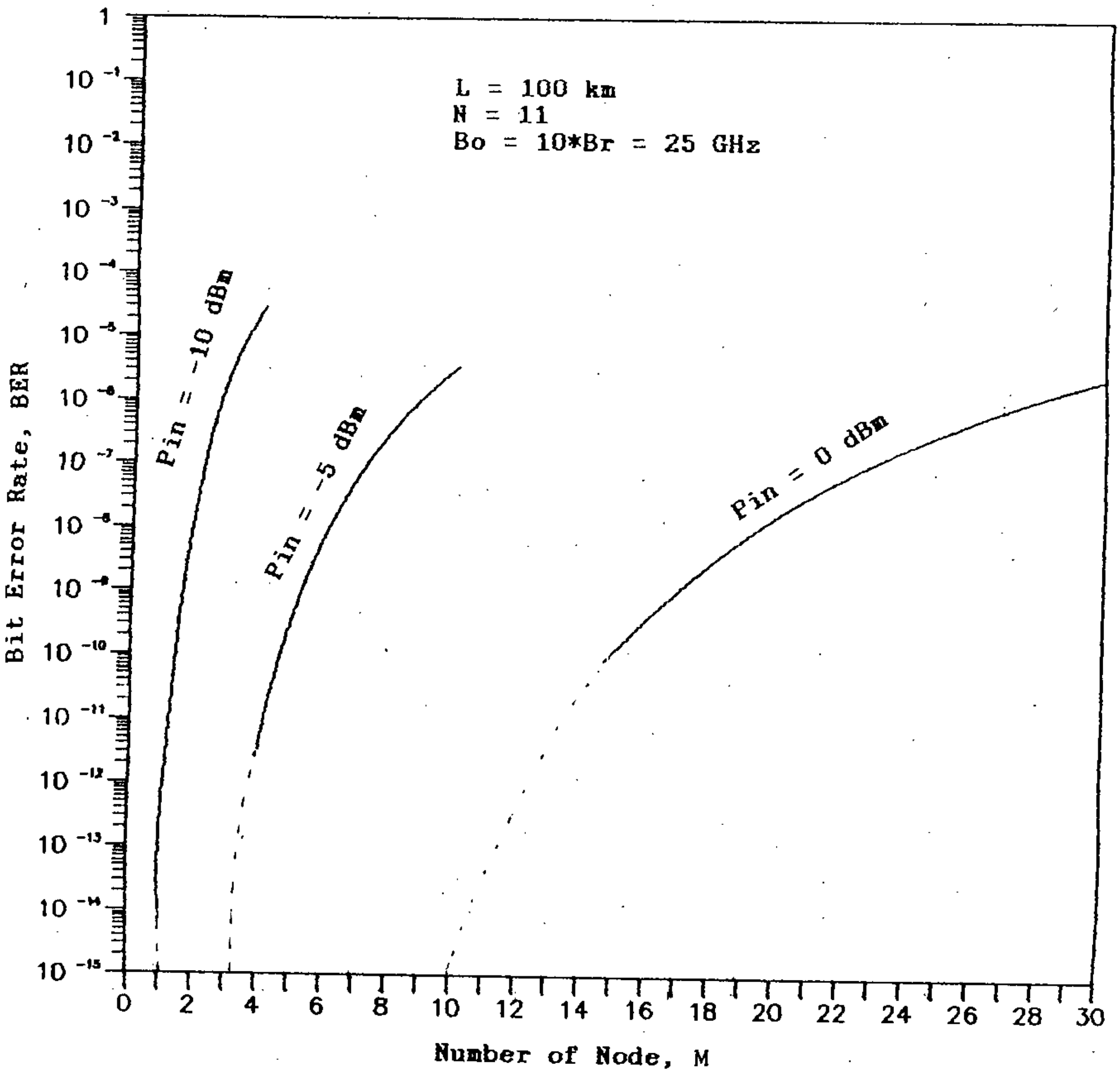

Fig.3.4 Bit error rate (BER) performance of optical MWTN at a bit rate of 2.5 Gb/s as a function of the number of nodes M when number of channels N=11, fiber span L=100 Km, B_o=10Br=25 GHz and P_{FWM}=0.0 for three different values of the optical transmitter power P_{in} (dBm).

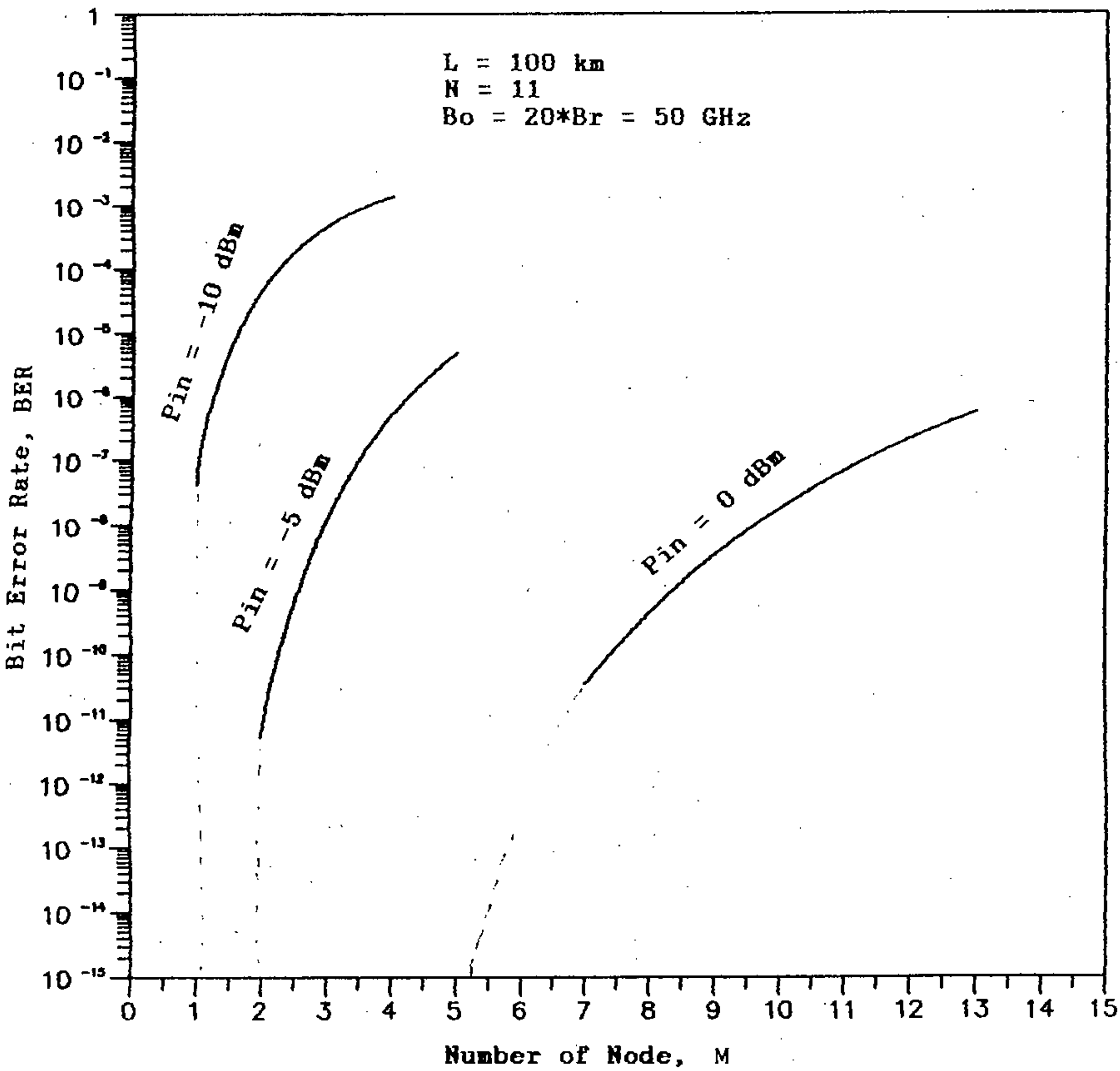

Fig.3.5 Bit error rate (BER) performance of optical MWTN at a bit rate of 2.5 Gb/s as a function of the number of nodes M when number of channels N=11, fiber span L=100 Km, B_o=20Br=50 GHz and P_{PWM}=0.0 for three different values of the optical transmitter power P_{in} (dBm).

The plots of the allowable number of nodes at BER = 10^{-9} versus the transmitter power P_{in} (dBm) is depicted in Fig. 3.6 with fiber span L as a parameter when B_o = 15 GHz. It is observed that as the input power increases the allowable number of nodes increases without limit due to increased receiver sensitivity. However, as the node separation or fiber span (L) is increased, the allowable number of nodes becomes drastically reduced. As is evident from the figure it is noticed that the number of allowable nodes is around 100 when L = 20 Km whereas it reduces to 10 when L is in increased to 100 Km. It is also observed that the product N.L $\leq$ 2000 when P_{in} = -5 dBm and reaches an upper limit of 6000 when P_{in} = 0 dBm.

For optical bandwidth, B_o = 10Br = 25 GHz, the variation of number of nodes at BER = 10^{-9} with input power P_{in} (dBm) is shown in Fig.3.7. Comparison of this curve with Fig.3.6 shows that the product NL is considerably less at higher optical bandwidth.

Similar observations are also found when B_o is increased to 50 GHz as shown in Fig.3.8.

The plots of allowable number of nodes at BER = 10^{-9} as a function of optical bandwidth B_o (GHz) is shown in Fig.3.9, Fig.3.10 and Fig.3.11 for L = 20 Km, 50 Km and 100 Km

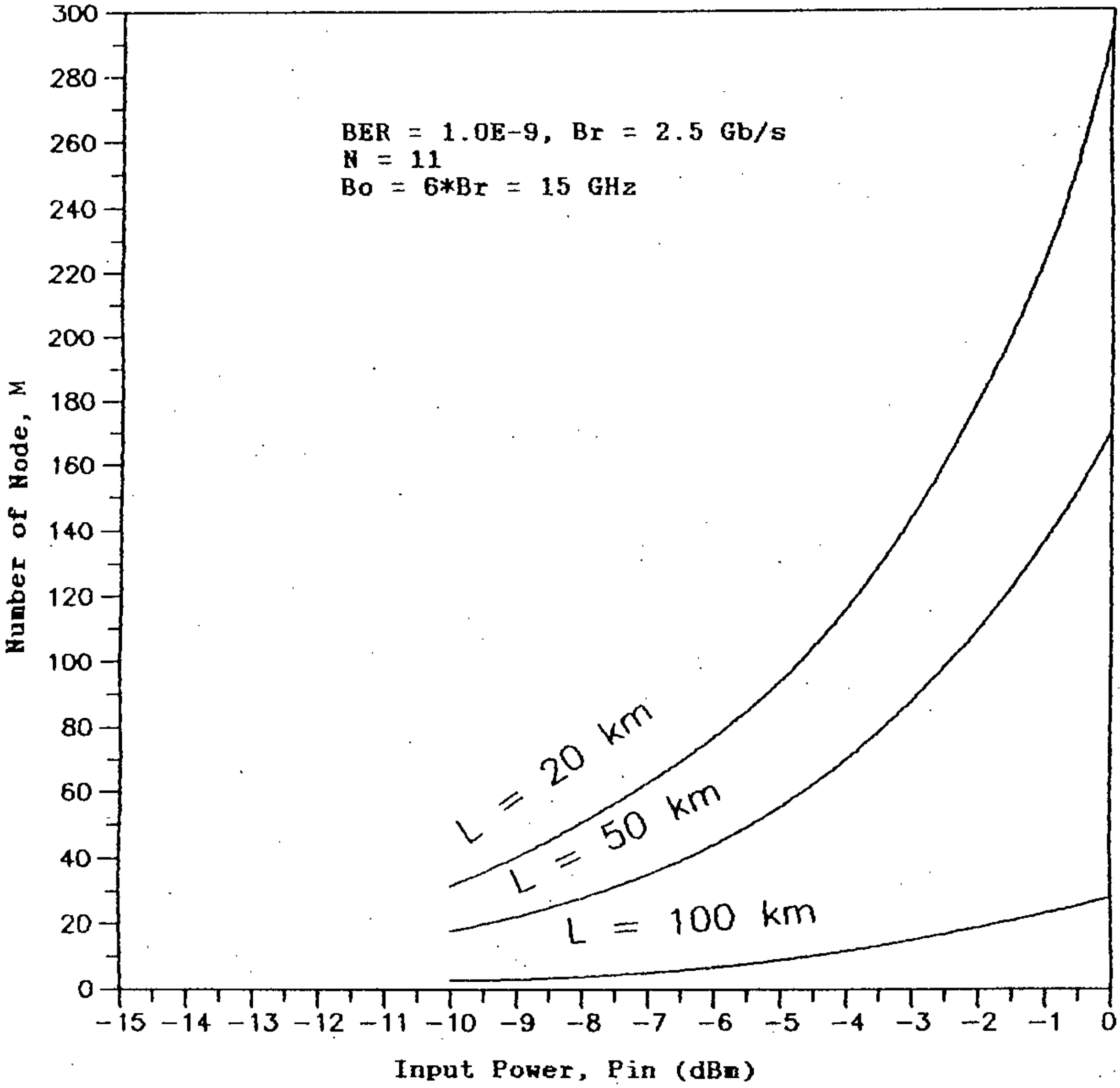

Fig.3.6 Plots of allowable maximum number of nodes M corresponding to BER of 10^{-9} as a function of the input transmitter power P_{in} (dBm) at a bit rate of 2.5 Gb/s and optical bandwidth B_o=6Br=15 GHz for three values of the fiber span L=20 Km, L=50 Km and L=100 Km, and P_{FWM}=0.0.

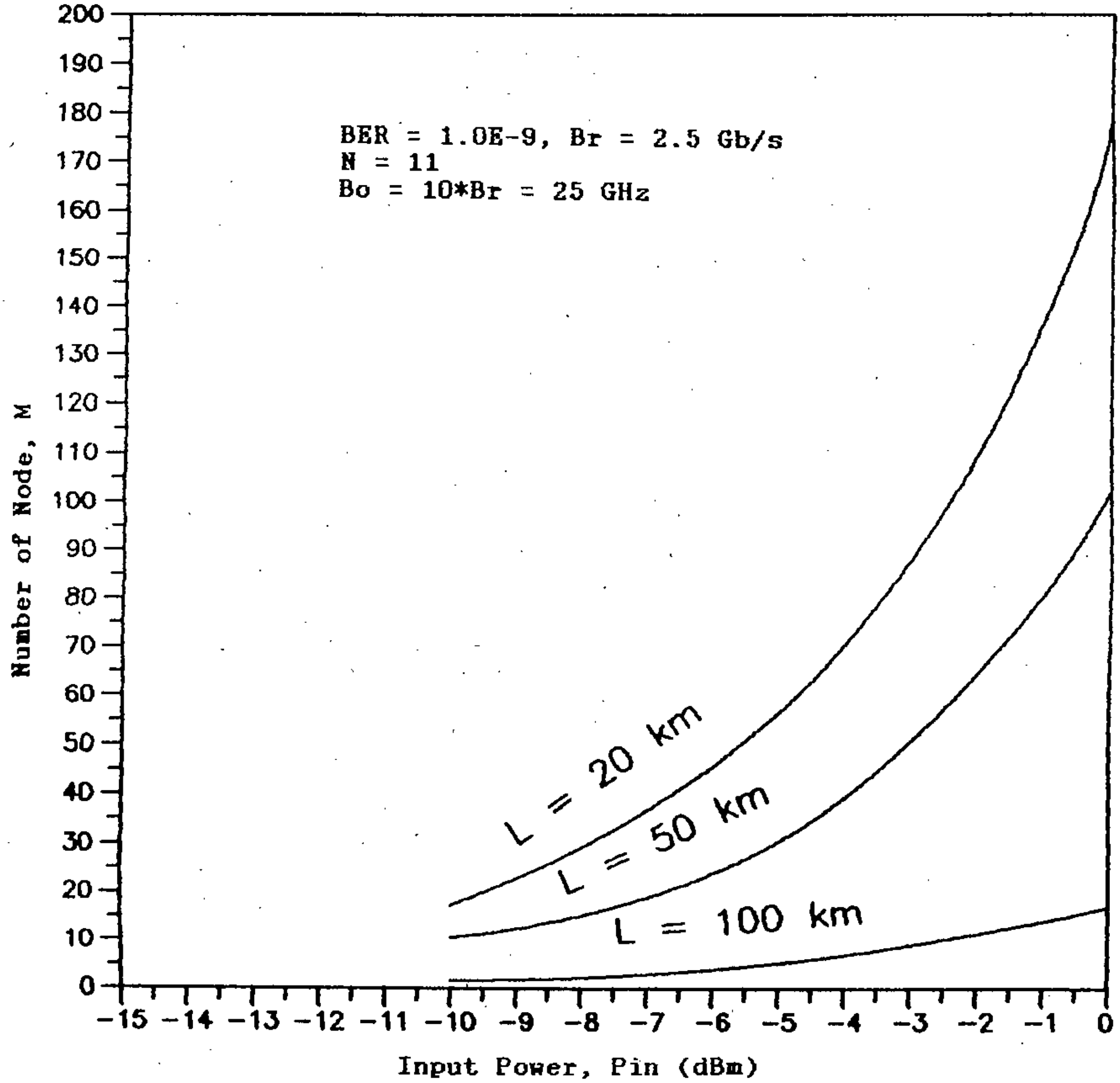

Fig.3.7 Plots of allowable maximum number of nodes M corresponding to BER of 10^{-9} as a function of the input transmitter power P_{in} (dBm) at a bit rate of 2.5 Gb/s and optical bandwidth B_o=10Br=25 GHz for three values of the fiber span L=20 Km, L=50 Km and L=100 Km, and P_{FWM}=0.0.

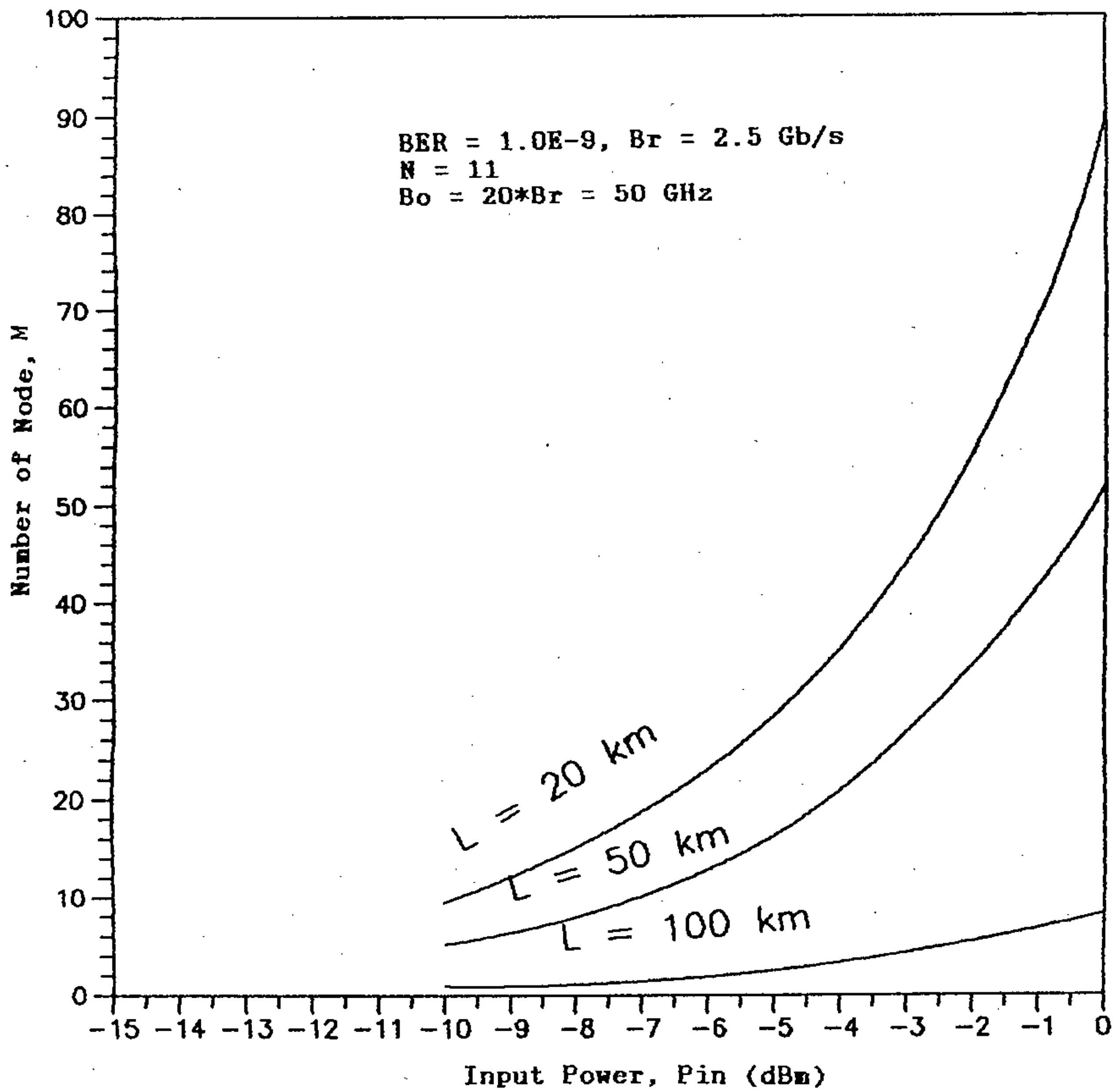

Fig.3.8 Plots of allowable maximum number of nodes M corresponding to BER of 10^{-9} as a function of the input transmitter power P_{in} (dBm) at a bit rate of 2.5 Gb/s and optical bandwidth B_o=20Br=50 GHz for three values of the fiber span L=20 Km, L=50 Km and L=100 Km, and P_{FWM}=0.0.

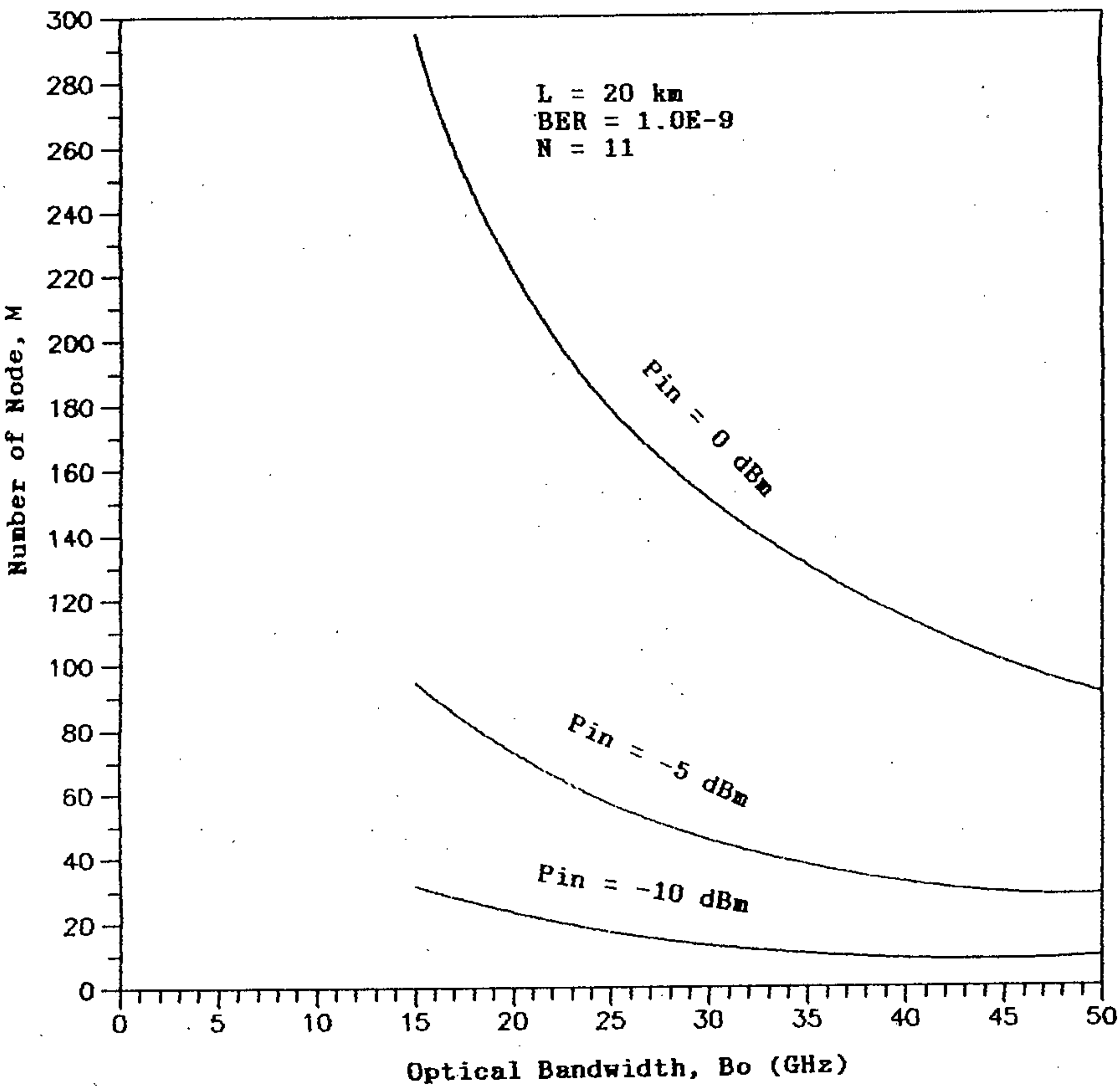

Fig.3.9 Variation of the allowable maximum number of nodes M as a function of optical bandwidth Bo for three values of the transmitter power P_{in} (dBm) at BER=10^{-9}, P_{FWM}=0.0 and fiber span L=20 Km.

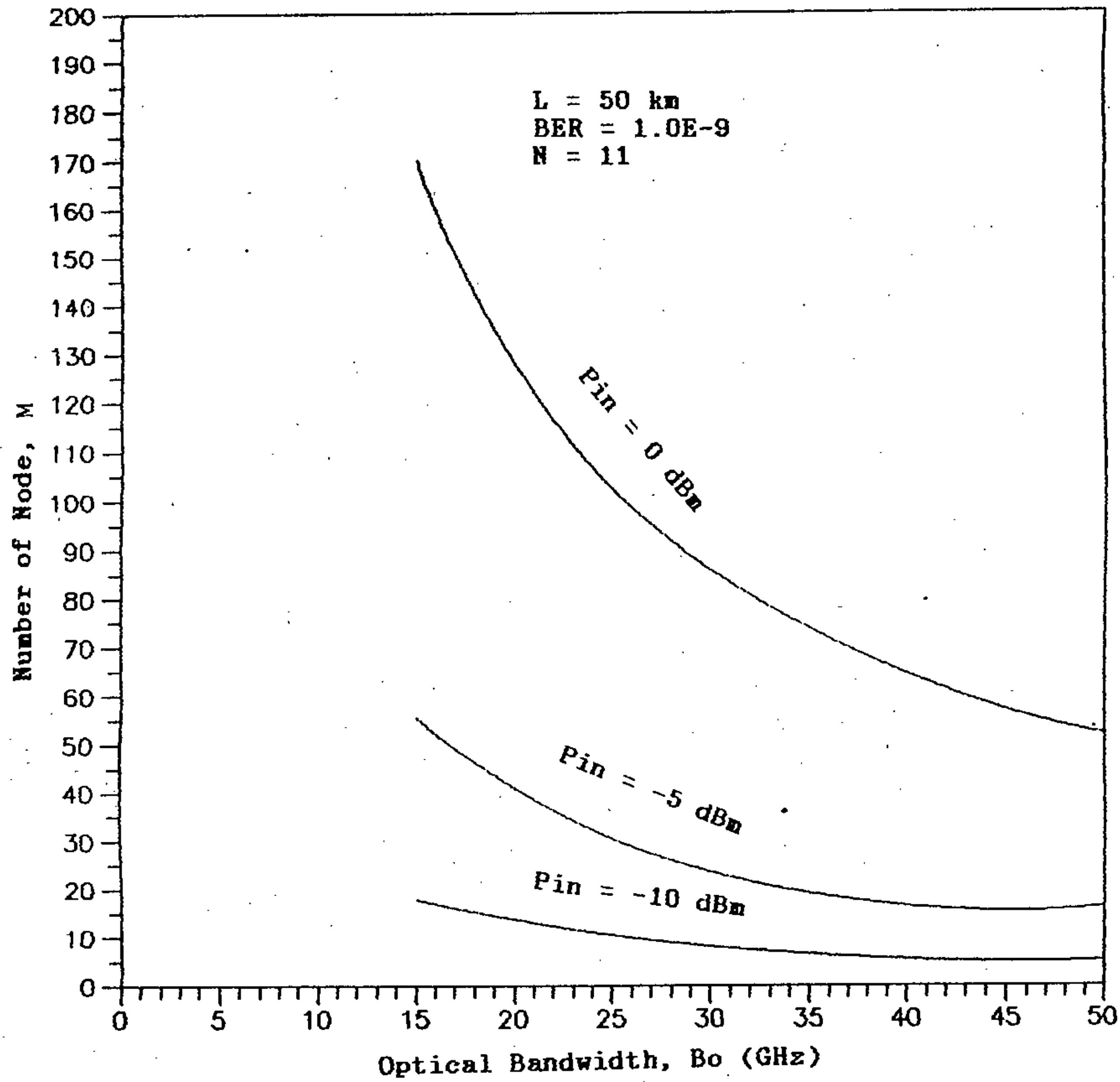

Fig.3.10 Variation of the allowable maximum number of nodes M as a function of optical bandwidth Bo for three values of the transmitter power P_{in} (dBm) at BER=10^{-9}, P_{FWM}=0.0 and fiber span L=50 Km.

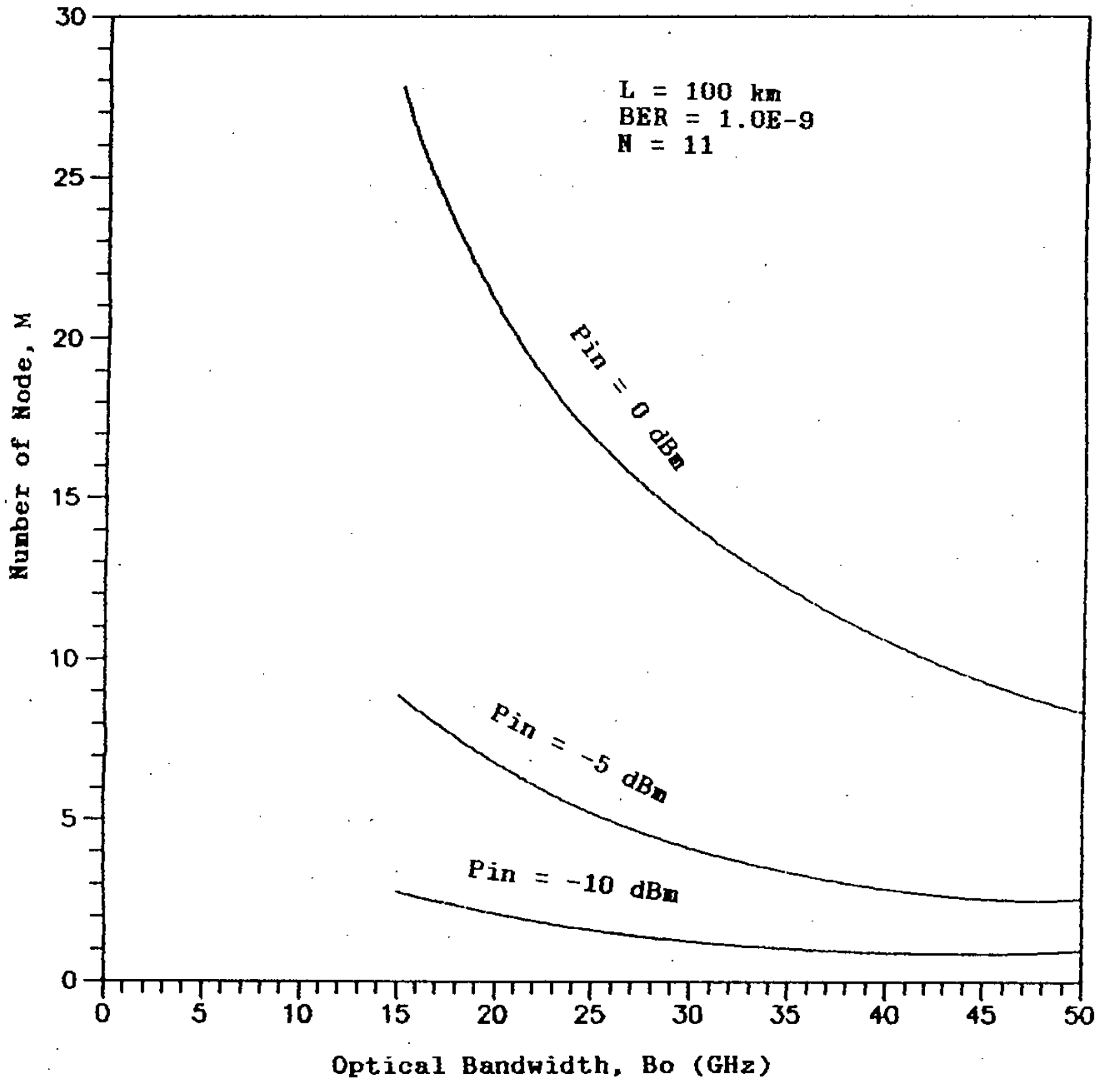

Fig.3.11 Variation of the allowable maximum number of nodes M as a function of optical bandwidth Bo for three values of the transmitter power P_{in} (dBm) at BER=10^{-9}, P_{FWM}=0.0 and fiber span L=100 Km.

respectively with P_{in} = -10, -5, and 0 dBm. The figures depict how the number of allowable nodes corresponding to BER = 10^{-9} varies with bandwidth of optical amplifier. However, the number of allowable nodes are higher at higher input power and are less at higher fiber length.

When FWM power is included, the BER performance results as a function of number of nodes M are depicted in Fig.3.12 when fiber span L = 20 Km, P_{in} = -5 dBm, B_o = 15 GHz for number of WDM channels N = 11, 51 and 101. The figure depicts the effect of FWM power on the system performance. As the number of channels N is increased at a given input power P_{in}, the BER performance of the system degrades due to increased FWM effect. When the input power is increased to -2.5 dBm, system performance improves in terms of number of nodes at a given BER as becomes evident from Fig.3.13. It is further noticed that at a given BER, the allowable number of nodes differ largely at higher input power P_{in}. This is due to the fact that for a given values of N, effect of FWM is more prominent at higher input optical power per channel. Similar observations are also found at higher input power, i.e., for P_{in} = -5.0 and -2.5 dBm as shown in Fig.3.14 and Fig.3.15.

The plots of allowable number of nodes M at BER = 10^{-9} as a function of input power P_{in} (dBm) is shown in Fig.3.16 for

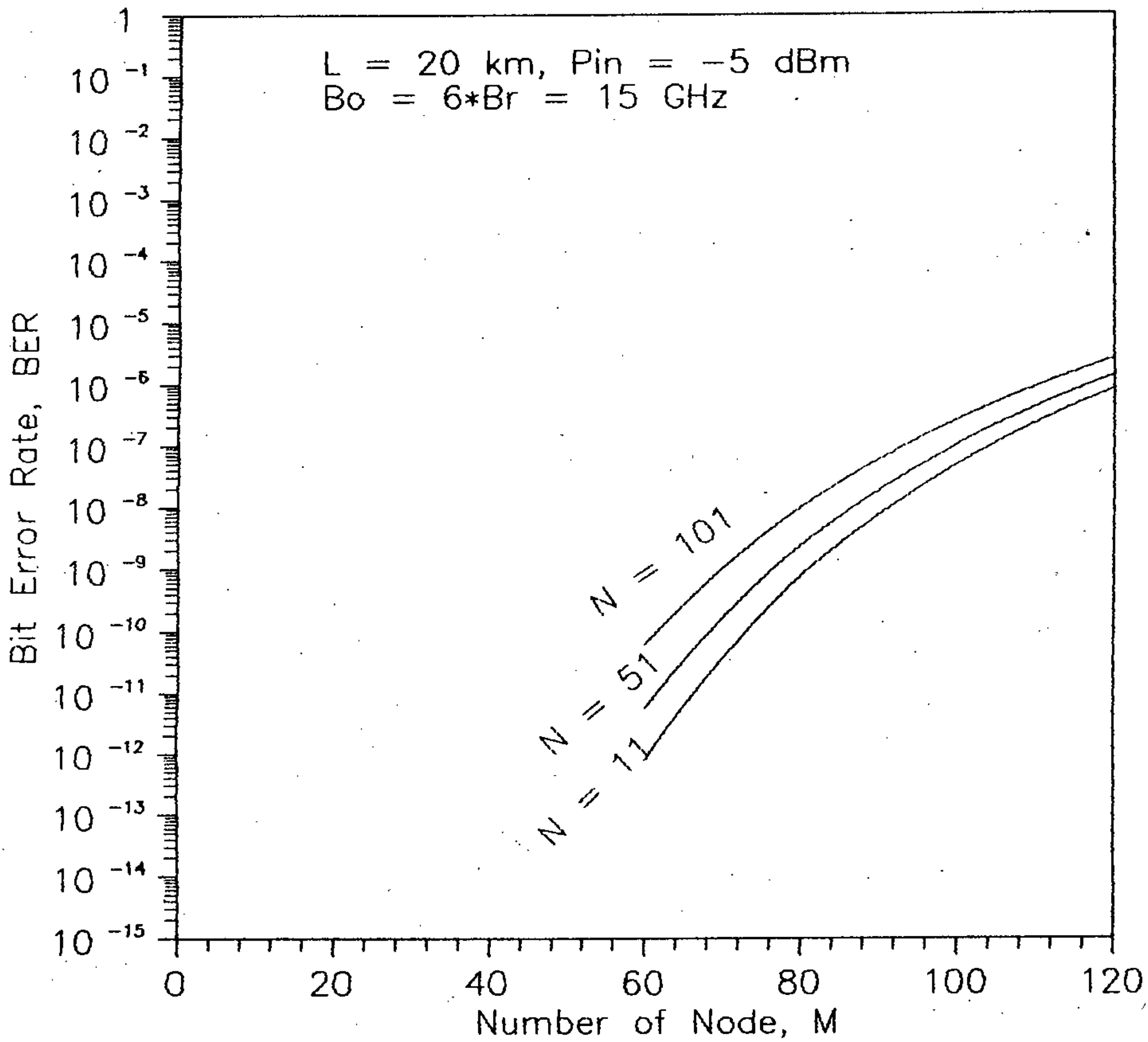

Fig.3.12 Bit error rate (BER) performance of optical MWTN versus number of nodes M, at a bit rate of 2.5 Gb/s for transmitter power P_{in} = -5 dBm and number of channels N=11, 51, 101 with L=20 Km and B_o=6Br=15 GHz.

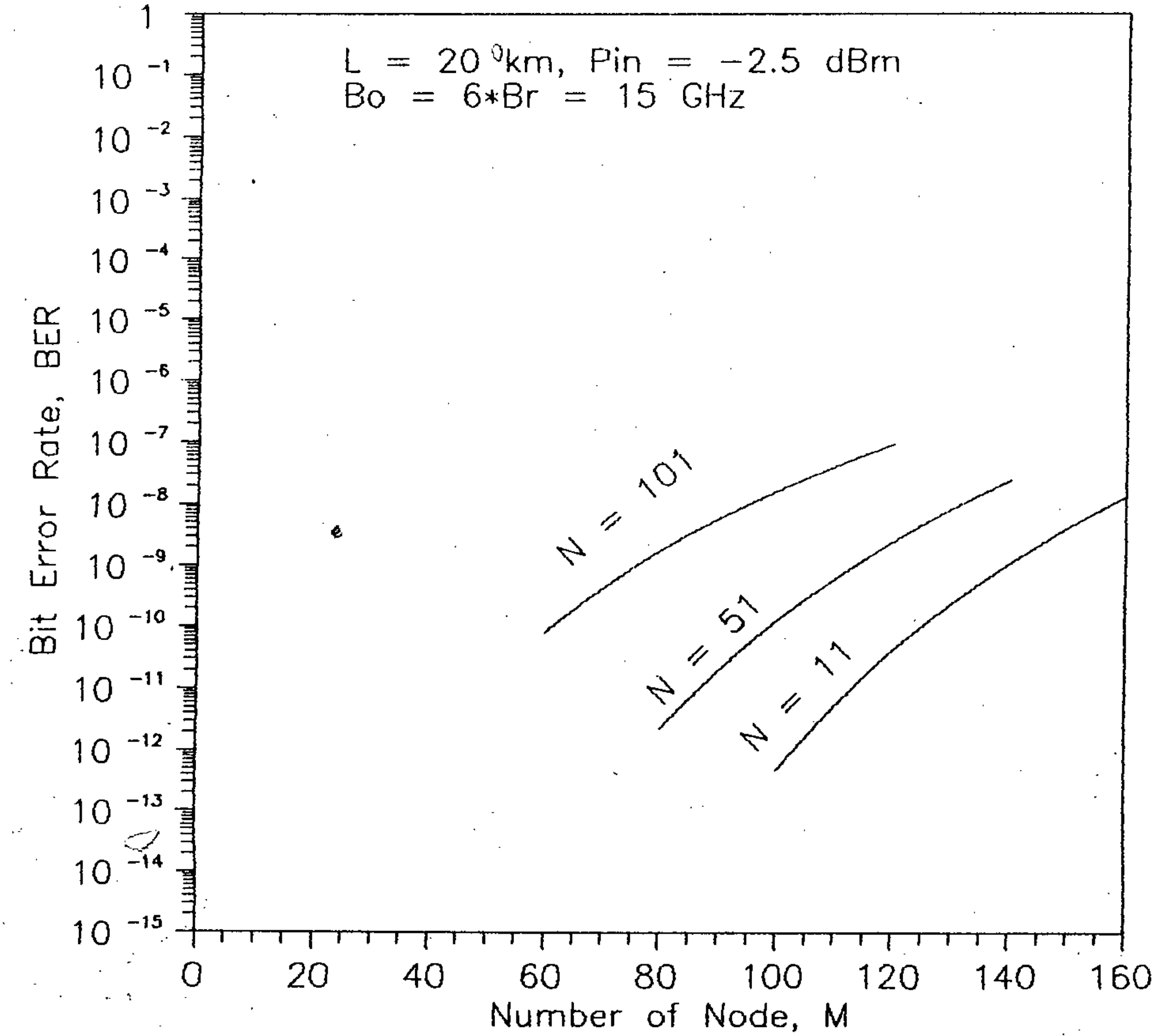

Fig.3.13 Bit error rate (BER) performance of optical MWTN versus number of nodes M, at a bit rate of 2.5 Gb/s for transmitter power P_{in} = −2.5 dBm and number of channels N=11, 51, 101 with L=20 Km and B_o=6Br=15 GHz.

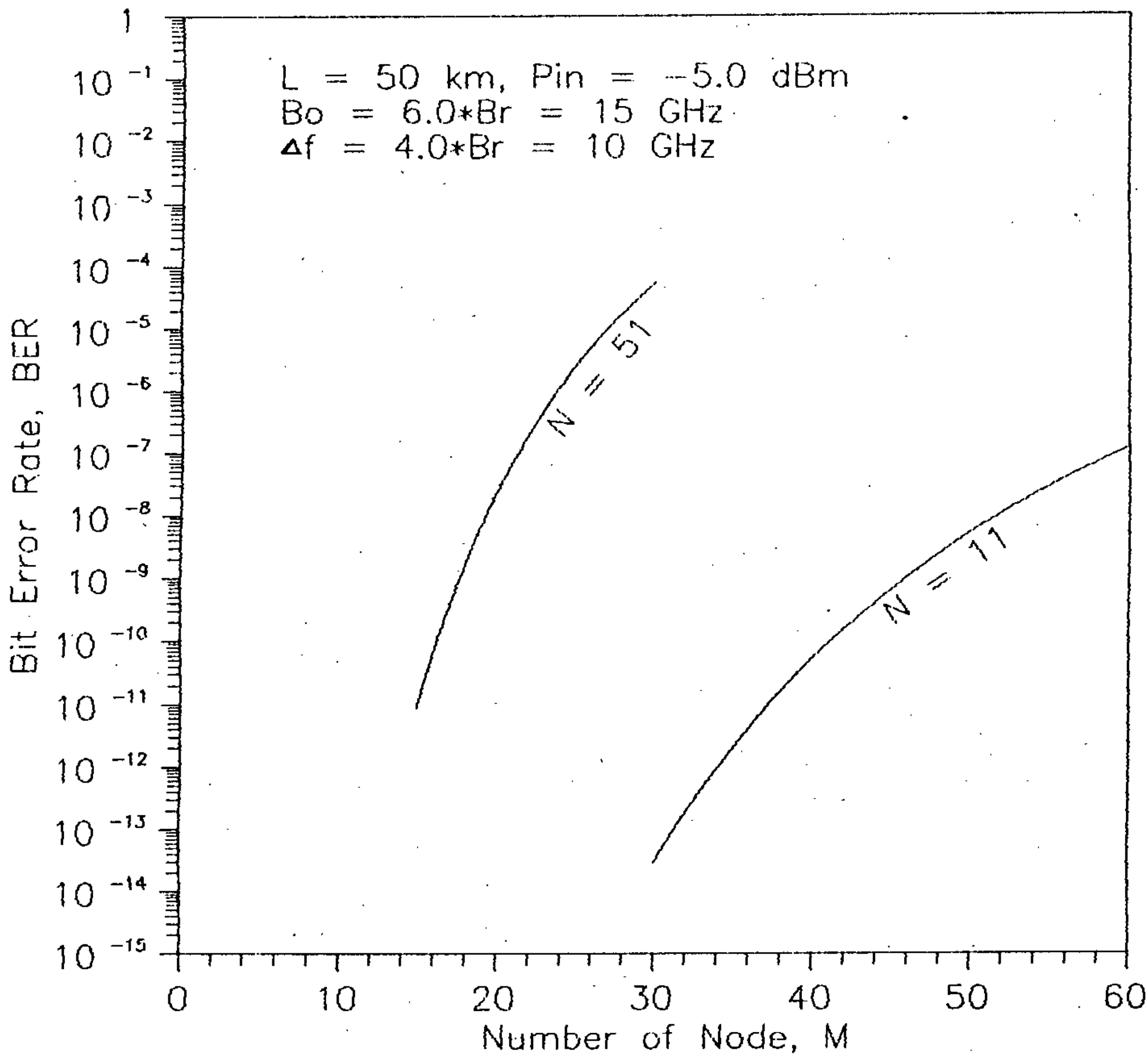

Fig.3.14 Bit error rate (BER) performance of optical MWTN versus number of nodes M, at a bit rate of 2.5 Gb/s for transmitter power P_{in} = -5 dBm and number of channels N=11 and 51 with L=50 Km and B_o=6Br=15 GHz.

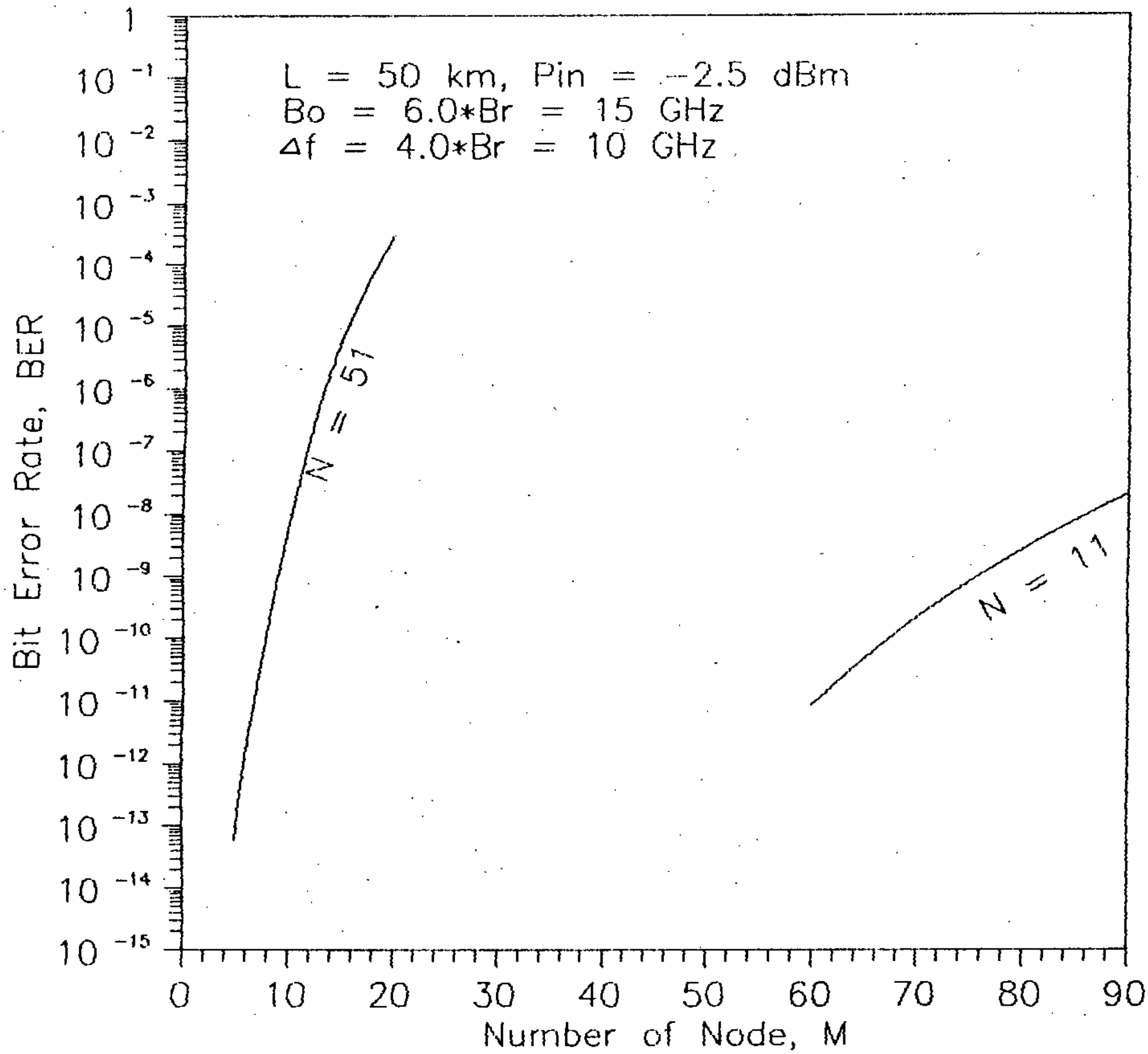

Fig.3.15 Bit error rate (BER) performance of optical MWTN versus number of nodes M, at a bit rate of 2.5 Gb/s for transmitter power P_{in} = -2.5 dBm and number of channels N=11 and 51 with L=50 Km and B_o=6Br=15 GHz.

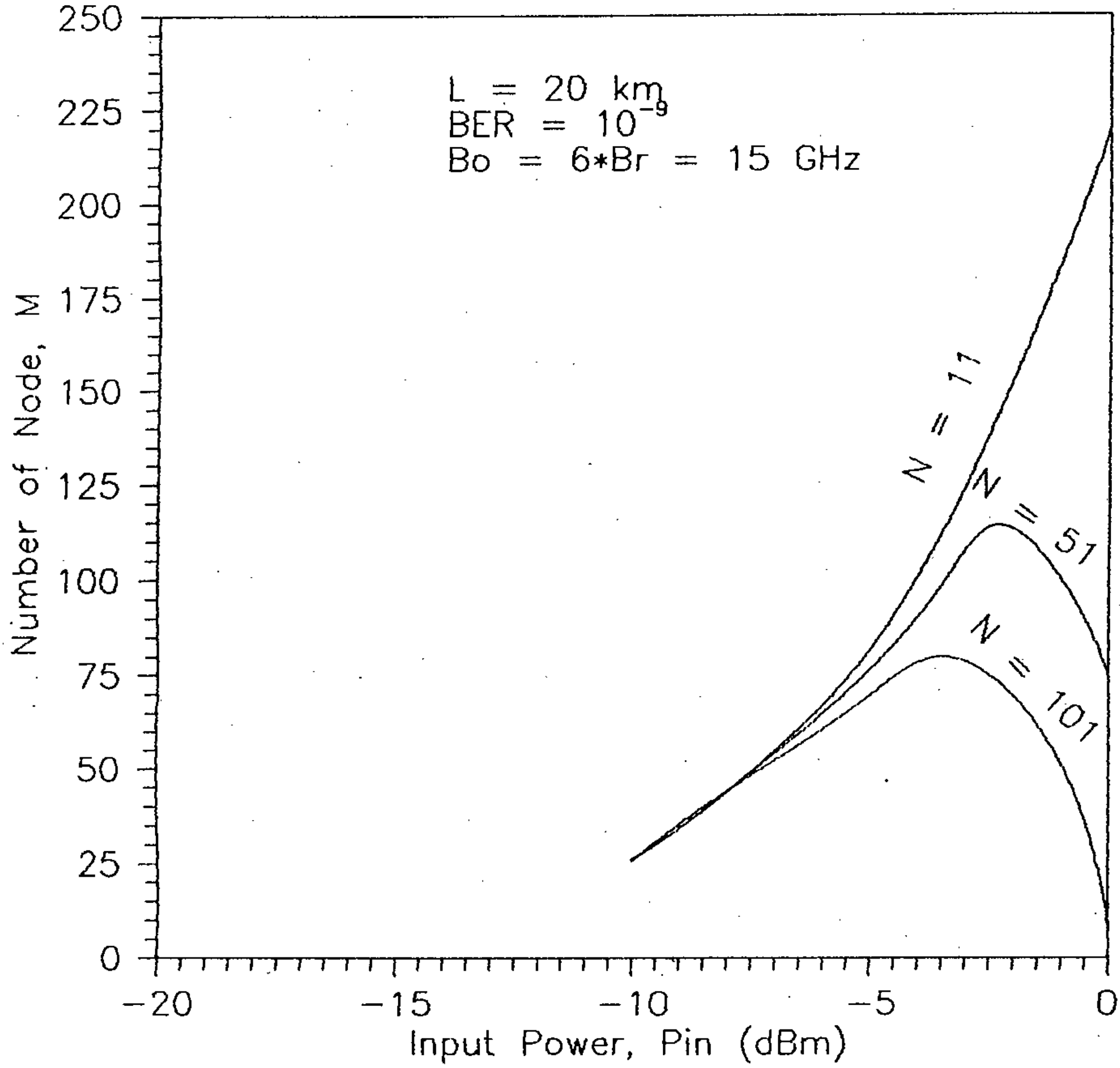

Fig.3.16 Plots of maximum allowable number of nodes M corresponding to BER of 10^{-9} as a function of the input transmitter power P_{in} (dBm) in the presence of four-wave mixing (FWM) effect at a bit rate of 2.5 Gb/s with optical bandwidth B_o=6Br=15 GHz and fiber span L=20 Km for number of channels N=11, 51, 101 and channel separation Δf=10 GHz.

three values of the number of channels N = 11, 51 and 101, when L = 20 Km, B_o = 15 GHz. The plots depict that the number of nodes increases with P_{in} but up to a certain limit where it reaches a maximum value at a given values of P_{in} and then decreases. This is due to the fact that as the input power increases, the receiver sensitivity and hence the allowable number of nodes increases and the receiver performance is limited by ASE and associated beat noise components. At increased P_{in}, the FWM power drastically increases with P_{in}^3 and as a consequence the system performance degrades and the allowable number of nodes is greatly reduced. Thus, there is a maximum value of the allowable number of nodes for a given value of the number of channels N which can be termed as M_{max}. The maximum value of M i.e., M_{max} is further reduced at increased values of the number of channels N. It is also evident that the maximum number of nodes M_{max} occurs corresponding to a maximum allowable input power $P_{in,max}$. The value of $P_{in,max}$ is less when the number of channels is increased.

Similar plots of allowable number of nodes M versus P_{in}(dBm) for higher fiber span e.g., L = 50 Km and 100 Km are provided in Fig.3.17 and Fig.3.18. Comparing these curves with Fig.3.16 we found that the maximum allowable node is greatly reduced at higher length of fiber span and the allowable

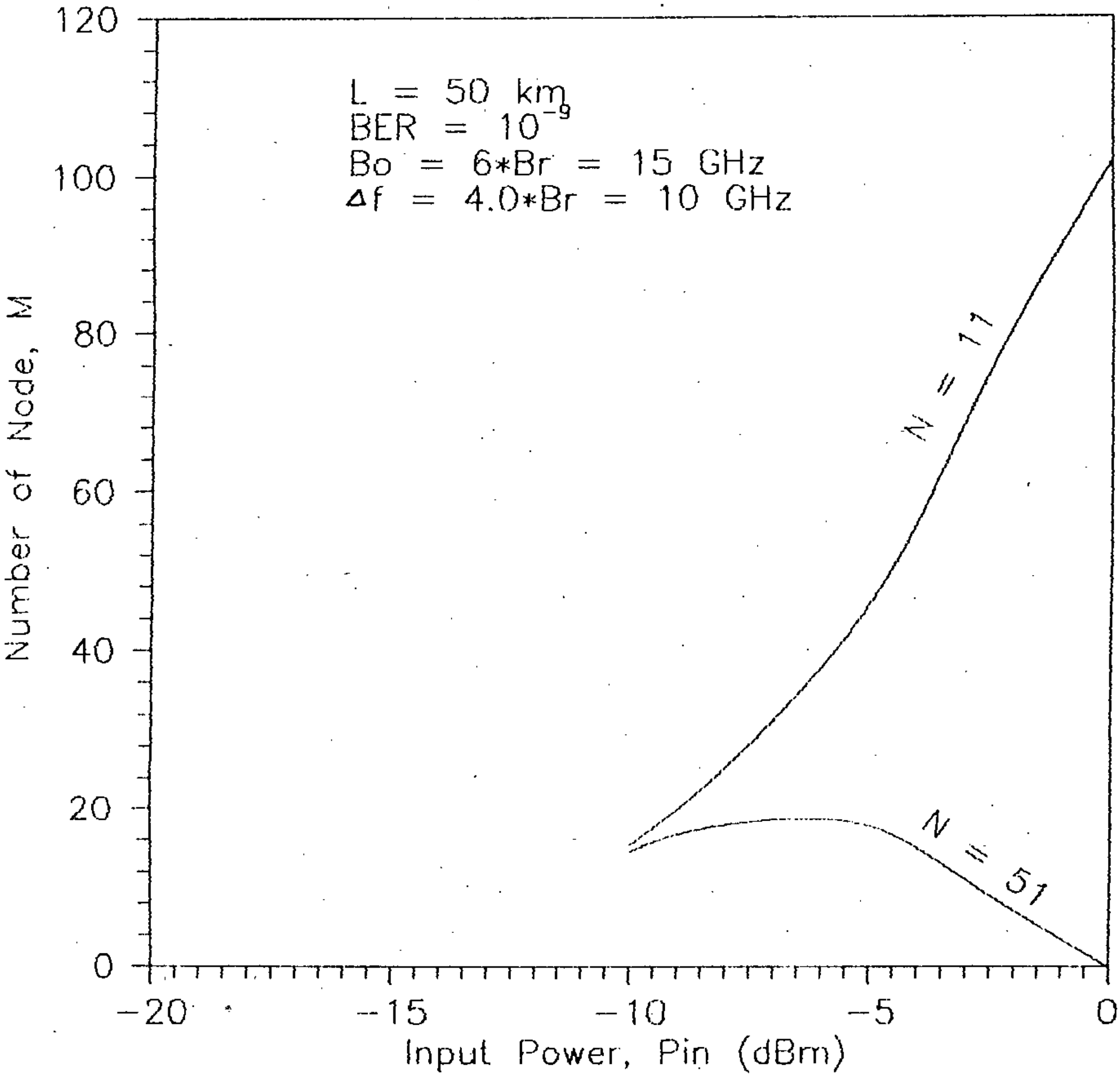

Fig.3.17 Plots of maximum allowable number of nodes M corresponding to BER of 10^{-9} as a function of the input transmitter power P_{in} (dBm) in the presence of four-wave mixing (FWM) effect at a bit rate of 2.5 Gb/ with optical bandwidth B_o=6Br=15 GHz and fiber span L=50 Km for number of channels N=11 and 51 and channel separation Δf=10 GHz.

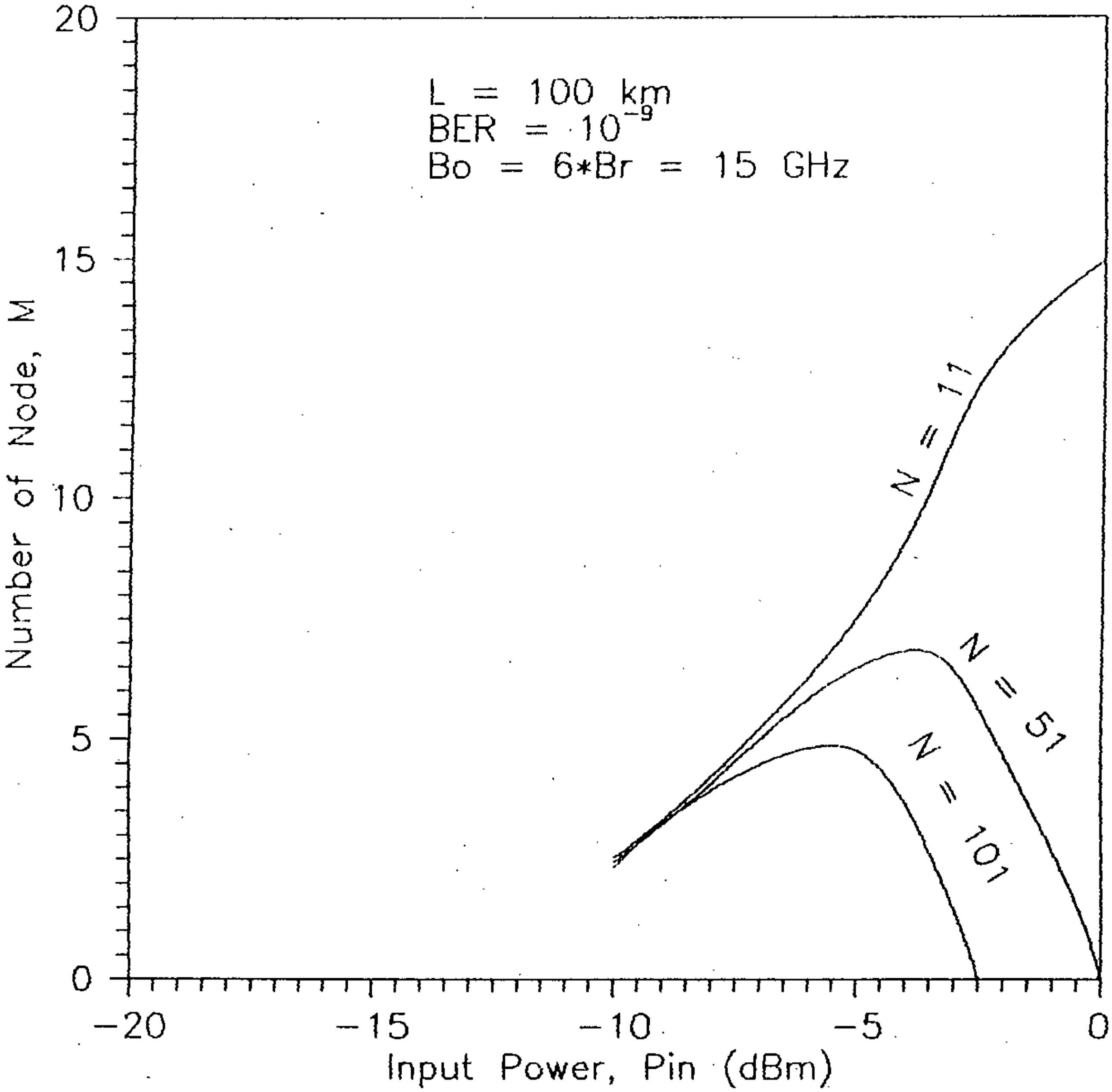

Fig.3.18 Plots of maximum allowable number of nodes M corresponding to BER of 10^{-9} as a function of the input transmitter power P_{in} (dBm) in the presence of four-wave mixing (FWM) effect at a bit rate of 2.5 Gb/s with optical bandwidth B_o=6Br=15 GHz and fiber span L=100 Km for number of channels N=11, 51, 101 and channel separation Δf=10 GHz.

maximum transmitter power $P_{in,max}$ is also less.

When the optical bandwidth B_o is increased, the plots of number of nodes M, corresponding to BER = 10^{-9}, versus P_{in}(dBm) for a given fiber span (L = 50 Km) is illustrated in Fig.3.19 and Fig.3.20 for B_o = 25 and 50 GHz respectively. It is noticed that there is a considerable reduction in the number of allowable nodes as B_o is increased from 25 GHz to 50 GHz due to increased ASE, FWM and beat noise components. The reduction is more pronounced at higher values of input power. Further, the maximum values of M i.e., M_{max} is also less at higher optical bandwidth.

Further, the maximum allowable number of nodes is further reduced when the frequency separation Δf between two adjacent channels is increased as depicted in Fig.3.21 with Δf = 50 GHz, L = 50 Km and B_o = 15 GHz. Comparison with Fig.3.17 when Δf = 15 GHz we see that the allowable number of nodes is considerably less at higher Δf.

In Fig.3.22 the allowable number of nodes at BER = 10^{-9} is plotted as a function of the number of channels N when L = 50 Km and B_o = 15 GHz for several input transmitter power. It is noticed that at a given input power, the number of nodes reduces with increasing values of the number of channels due

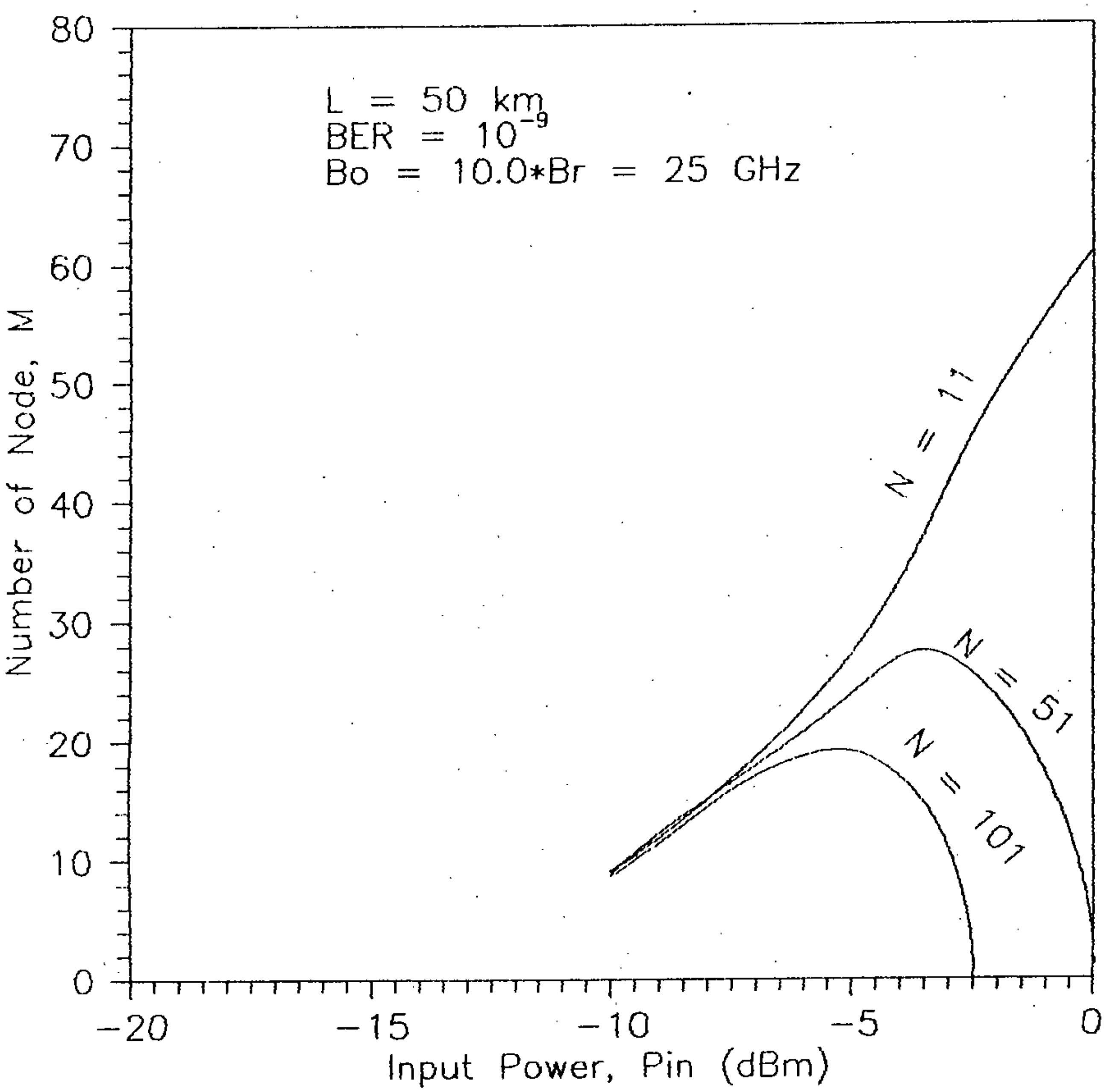

Fig.3.19 Plots of maximum allowable number of nodes M corresponding to BER of 10^{-9} as a function of the input transmitter power P_{in} (dBm) in the presence of four-wave mixing (FWM) effect at a bit rate of 2.5 Gb/s with optical bandwidth B_o=10Br=25 GHz and fiber span L=50 Km for number of channels N=11, 51, 101 and channel separation Δf=10 GHz.

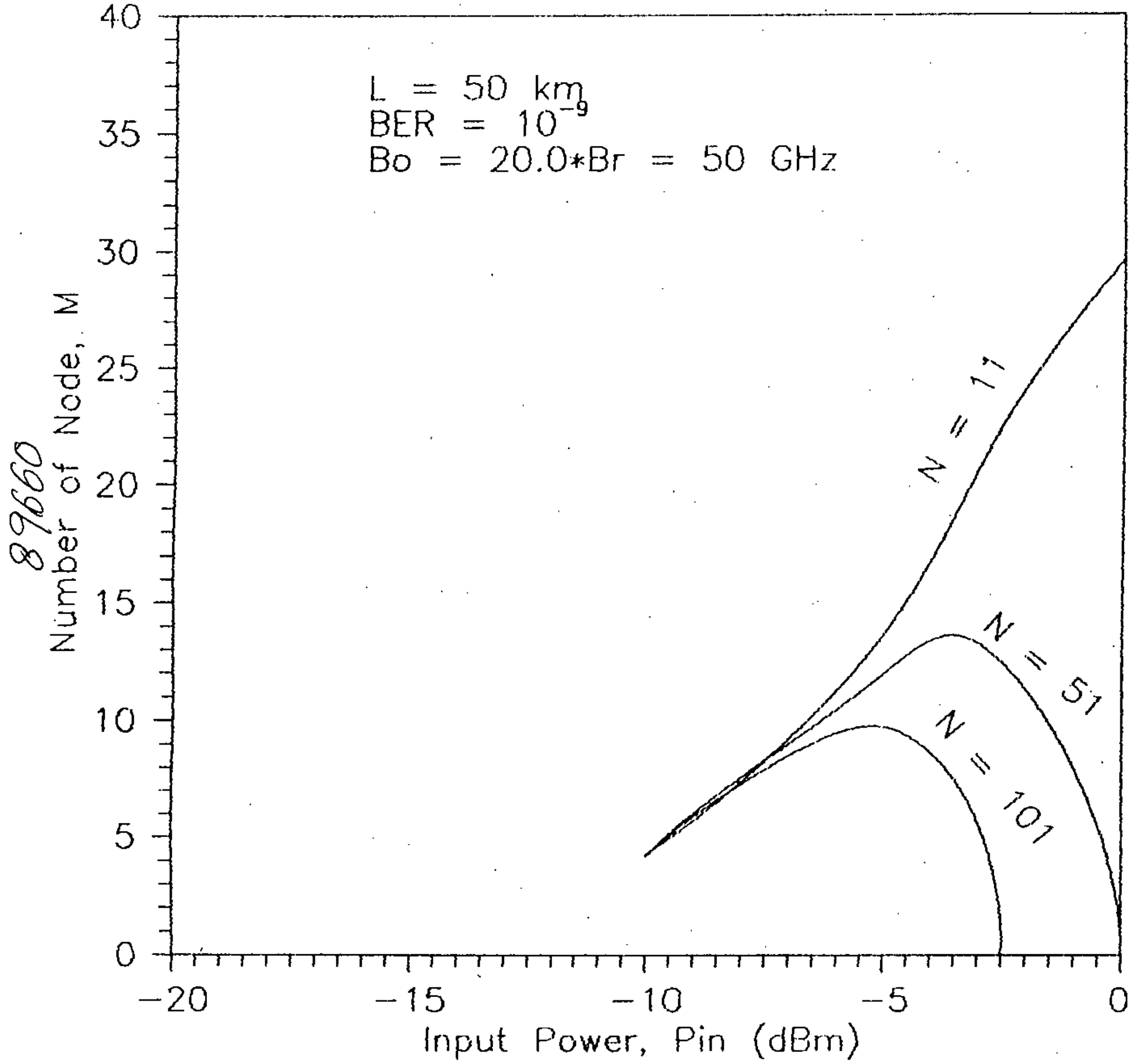

Fig.3.20 Plots of maximum allowable number of nodes M corresponding to BER of 10^{-9} as a function of the input transmitter power P_{in} (dBm) in the presence of four-wave mixing (FWM) effect at a bit rate of 2.5 Gb/s with optical bandwidth B_o=20Br=50 GHz and fiber span L=50 Km for number of channels N=11, 51, 101 and channel separation Δf=10 GHz.

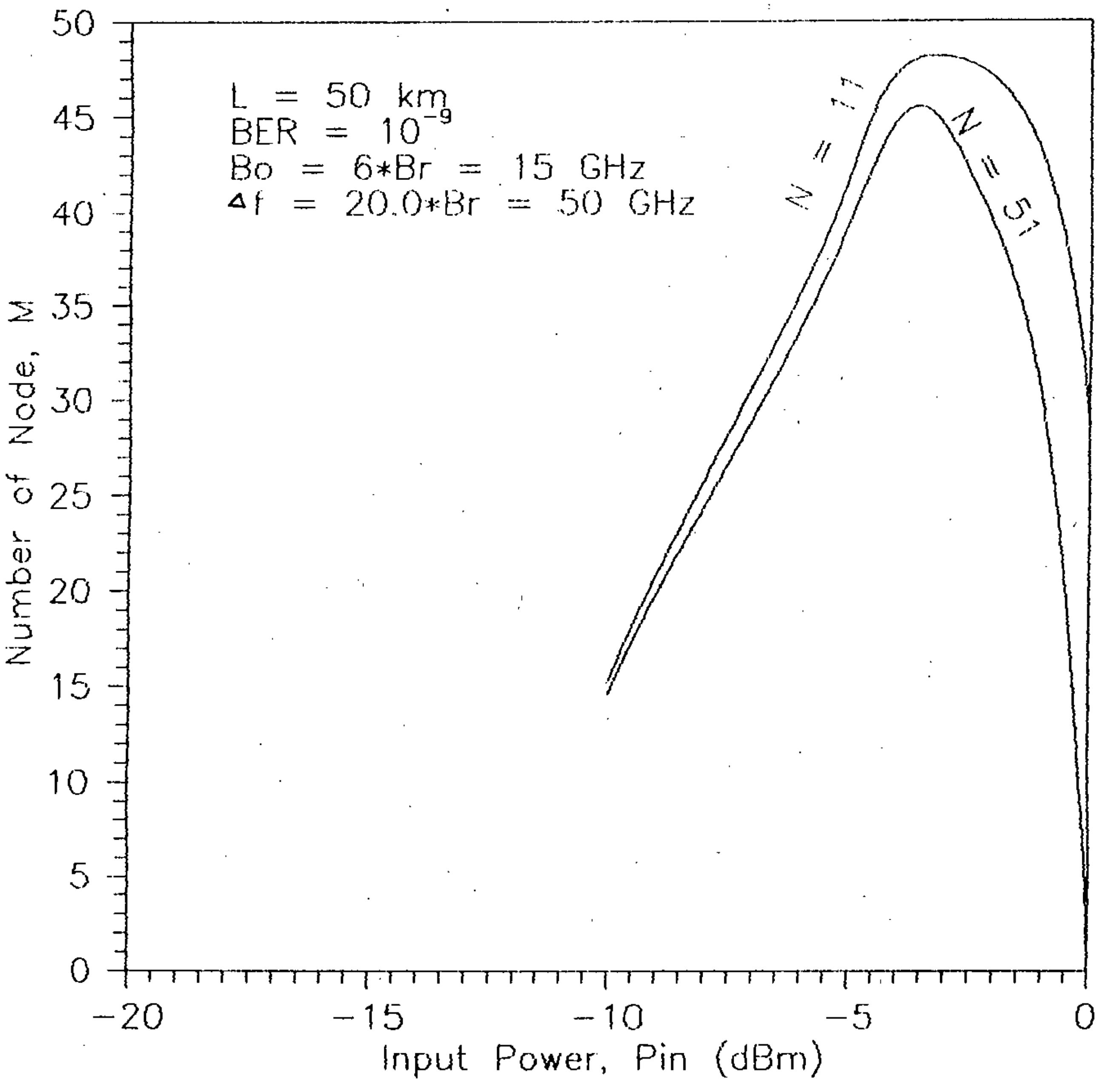

Fig.3.21 Variation of the allowable number of nodes M at BER=10^{-9} versus the transmitter power P_{in} (dBm) in the presence of FWM effect when the number of channels N=11 and 51 and channel separation Δf=50 GHz, B_o=15 GHz and fiber span, L=20 Km.

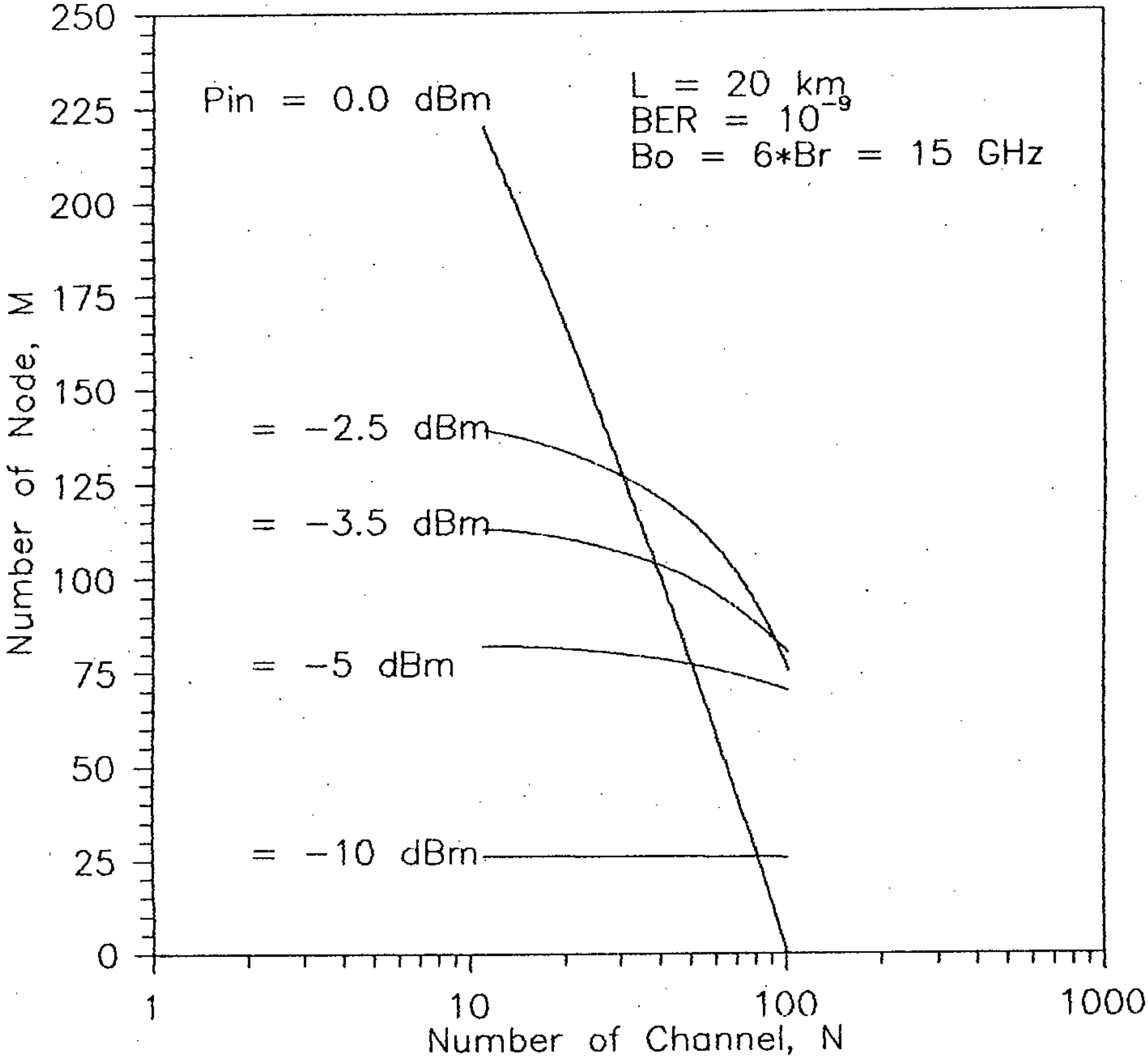

Fig.3.22 Plots of maximum allowable number of nodes M in presence of FWM effect at a bit error rate (BER) of 10^{-9} as a function of the number of WDM channels, N when channel separation is 10 GHz and and L=20 Km for different values of transmitter power P_{in} (dBm).

to increased FWM effect. The rate at which the number of nodes M decreases depends on input power P_{in}. The reduction is more rapid at higher optical input power and at low value of input power number of nodes M is almost independent of number of channels N. Similar curves of M vs. N for higher span length L and higher optical bandwidth B_o are shown in Fig.3.23 and Fig.3.24 respectively. The figures reveal similar behavior and indicate how the number of allowable nodes is greatly reduced due to increased fiber length and/or increased optical bandwidth.

The maximum achievable number of nodes at BER = 10^{-9} and at a given fiber span L and given value of the number of channels N is plotted against the channel separation Δf (GHz) in Fig.3.25 and Fig.3.26 with input optical power P_{in} as a parameter. These curves illustrate the dependence of FWM effect (and/or maximum allowable number of nodes M_{max}) on the channel separation. It becomes clear that as the channel separation increases, the value of M_{max} increases, attains a maximum value corresponding to a certain value of Δf and then again decreases. The nature of the curve is due to the dependence of FWM phase $\Delta\beta$ on the channel separation Δf.

Fig.3.27 depicts the variation of maximum allowable number of nodes, M_{max} with optical bandwidth B_o for number of channels

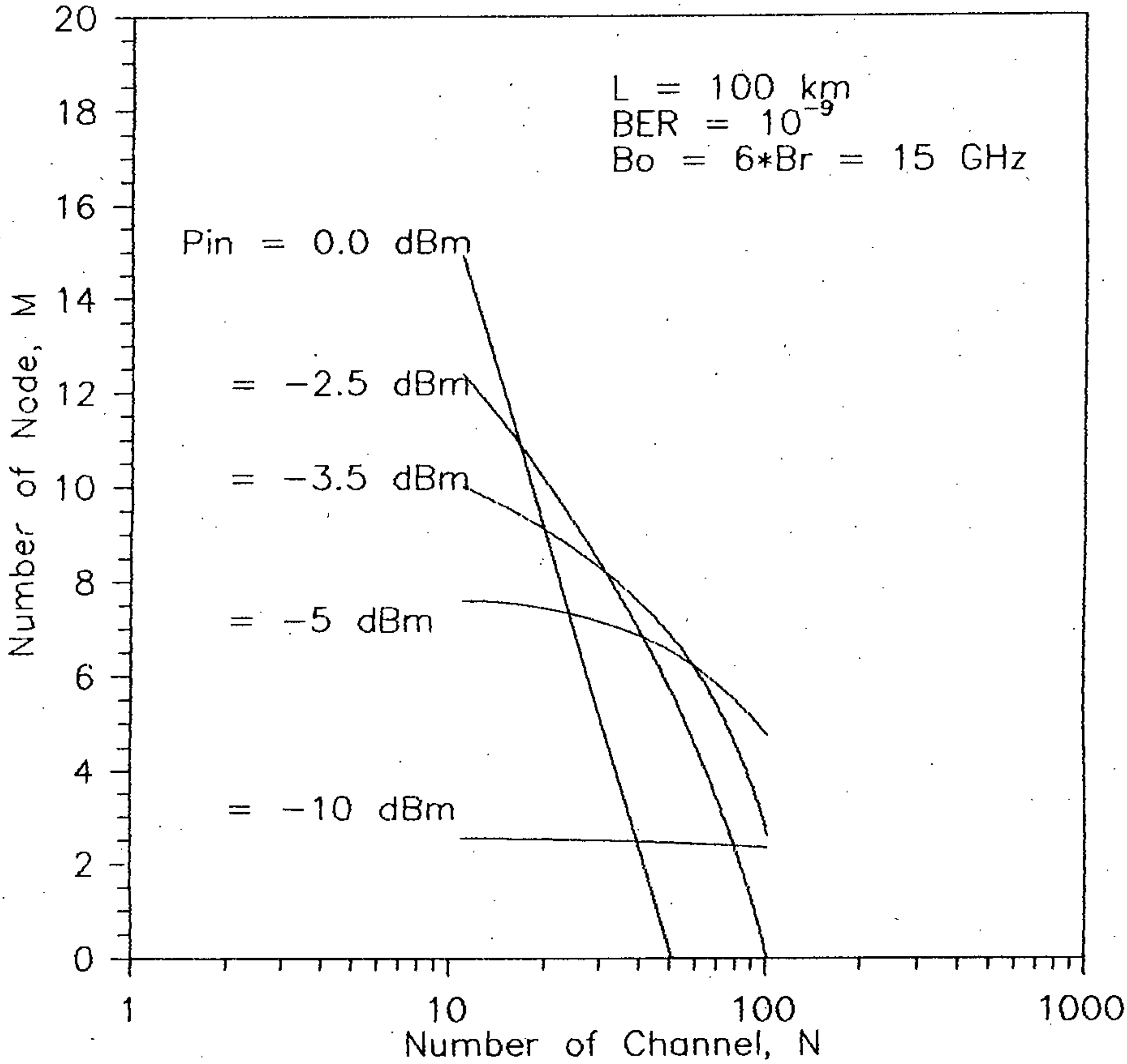

Fig.3.23 Plots of maximum allowable number of nodes M in presence of FWM effect at a bit error rate (BER) of 10^{-9} as a function of the number of WDM channels, N when channel separation is 10 GHz and and L=100 Km for different values of transmitter power P_{in} (dBm).

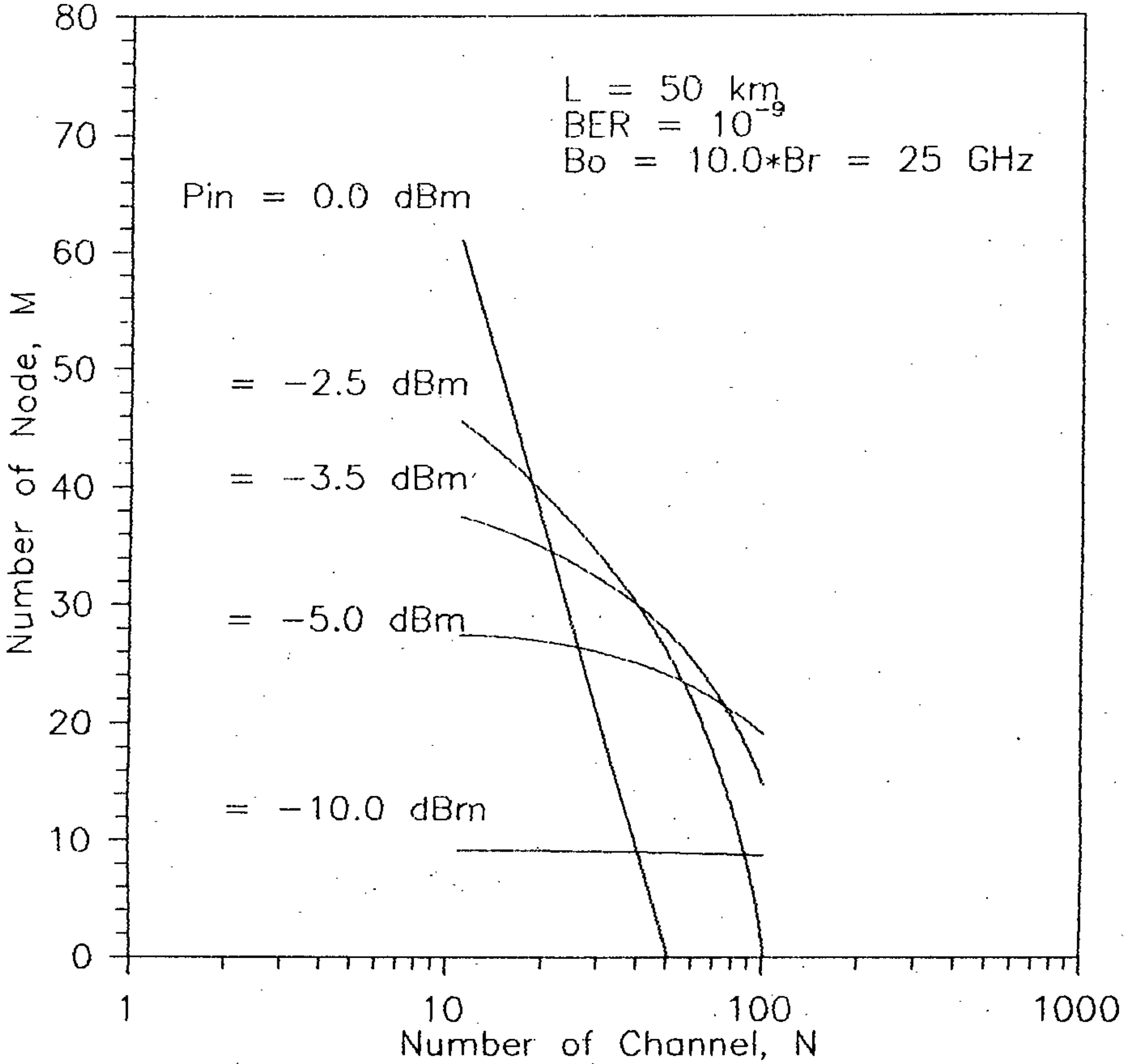

Fig.3.24 Plots of maximum allowable number of nodes M in presence of FWM effect at a bit error rate (BER) of 10^{-9} as a function of the number of WDM channels, N when channel separation is 10 GHz and and L=50 Km and B_o=10Br=25 GHz for different values of transmitter power P_{in} (dBm).

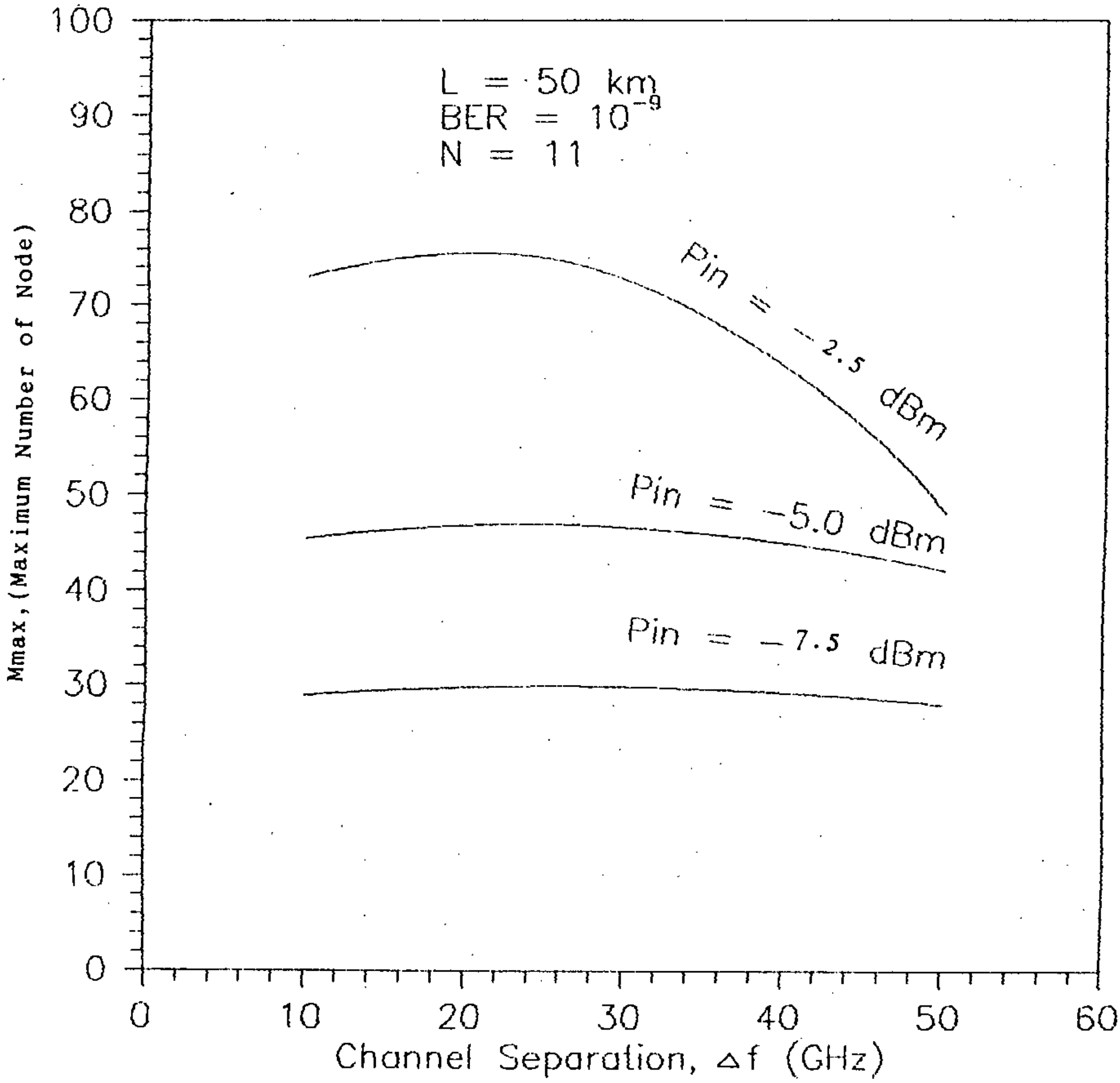

Fig.3.25 Plots of the allowable maximum number of nodes Mmax at BER=10^{-9} as a function of channel separation Δf in the presence of FWM effect when the number of WDM channels N=11 and fiber span L=50 Km for P_{in} = -2.5, -5.0, -7.5 dBm.

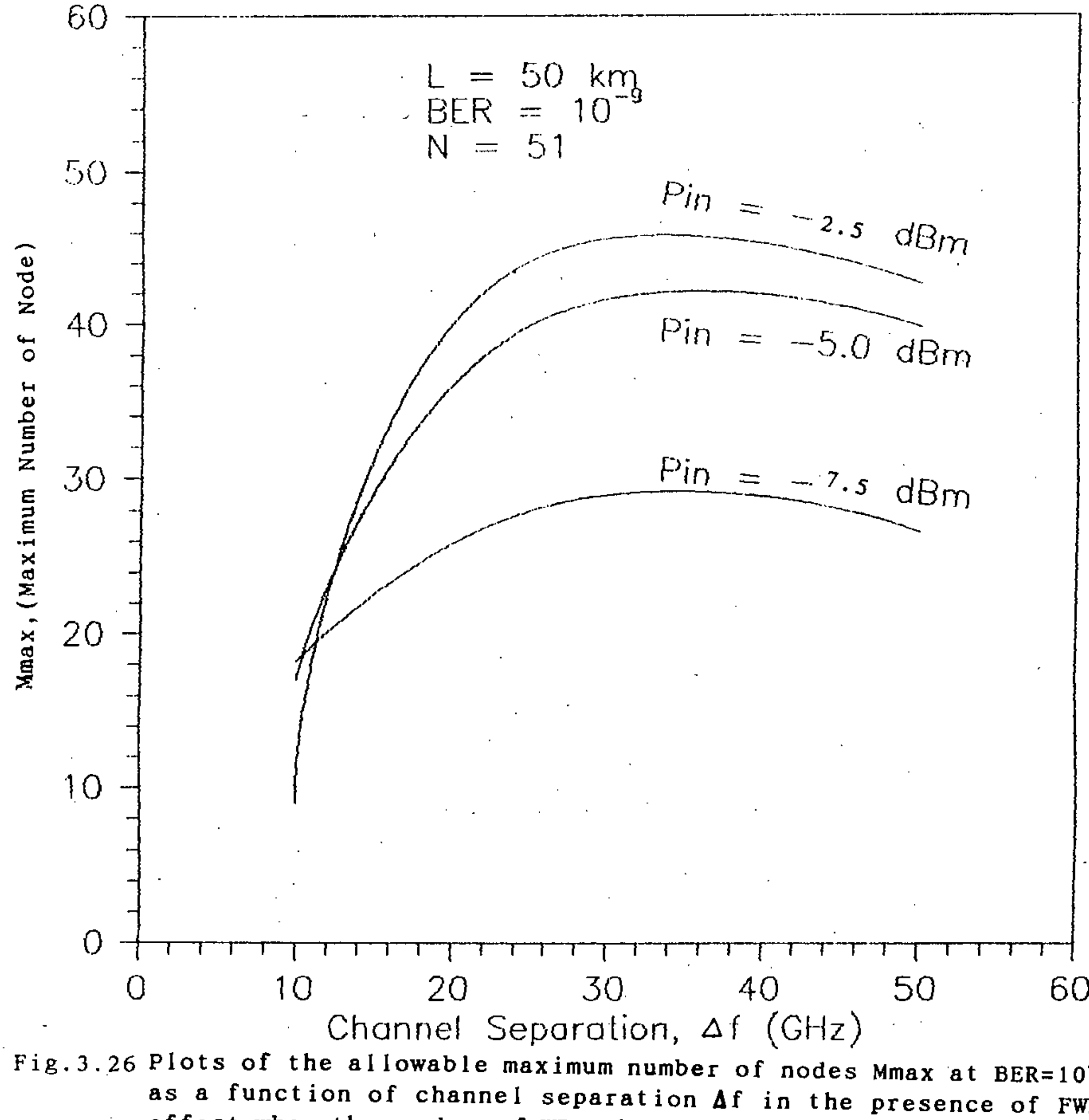

Fig.3.26 Plots of the allowable maximum number of nodes Mmax at $BER=10^{-9}$ as a function of channel separation Δf in the presence of FWM effect when the number of WDM channels N=51 and fiber span L=50 Km for P_{in} = -2.5, -5.0, -7.5 dBm.

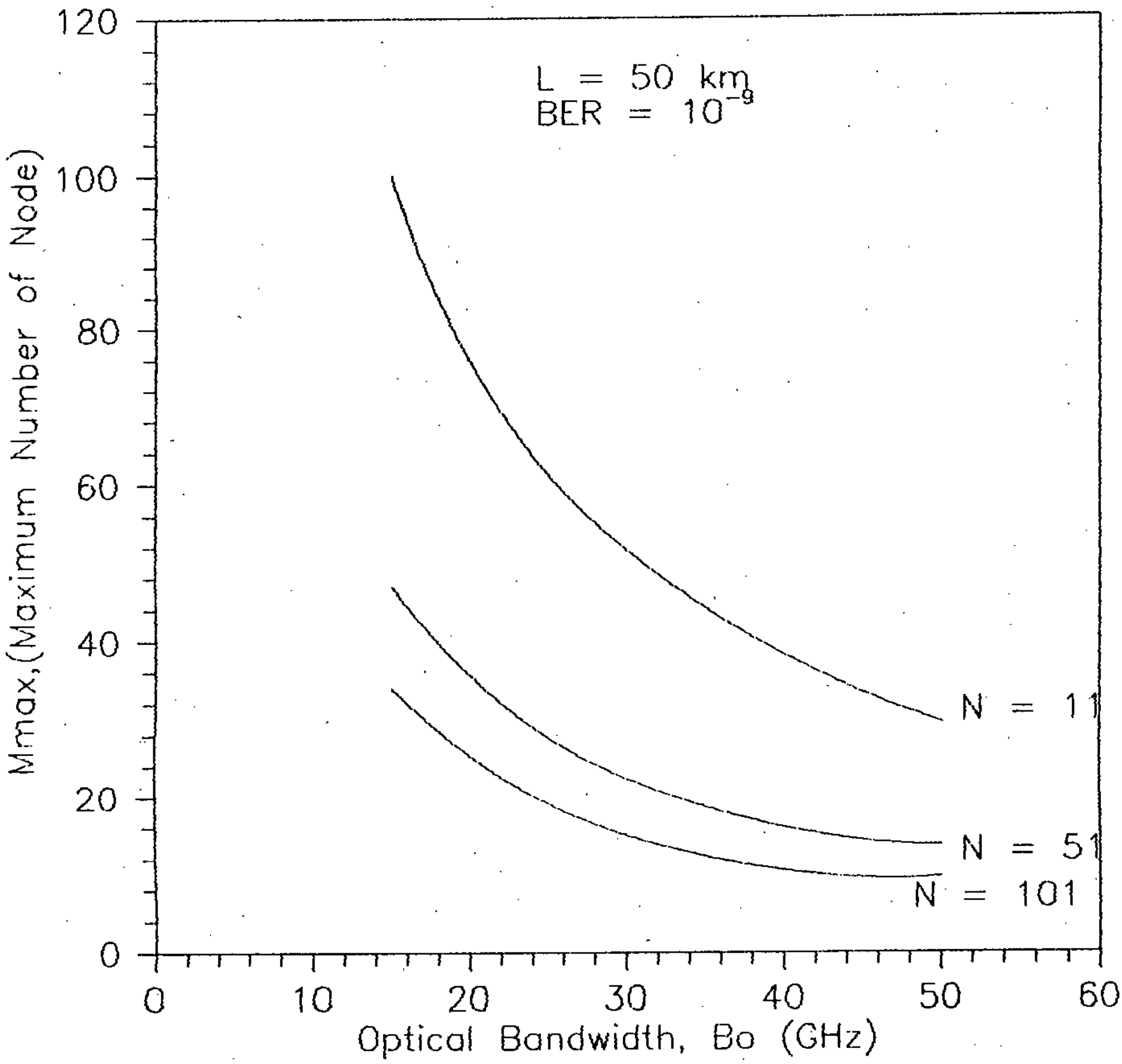

Fig.3.27 Plots of the ultimate maximum number of nodes Mmax, versus optical bandwidth B_o (GHz) at BER=10^{-9} in the presence of FWM effect for three different values of the number of WDM channels N=11, 51, 101 when fiber span L=50 Km and channel separation Δf=25 GHz.

$N = 11$, 51 and 101. Again it is clearly noticed that M_{max} decreases exponentially with increased optical bandwidth.

The maximum allowable optical input power, $P_{in,max}$ corresponding to M_{max} at BER = 10^{-9} is plotted against B_o (GHz) in Fig.3.28. It is found that $P_{in,max}$ is higher at lower values of N and is greatly reduced at higher value of N and is almost independent on B_o which is also evident from Fig.3.29.

In Fig.3.30, the maximum allowable number of nodes is plotted as a function of number of channels N for B_o = 15, 25 and 50 GHz and L = 50 Km. This figure reveals that M_{max} is reduced greatly at higher values of N, and higher optical bandwidth. Similar observations are also found in Fig.3.31 where M_{max} is plotted against N for L = 20, 50 and 100 Km.

Fig.3.32 depicts the variation of $P_{in,max}$ with N for three values of fiber span, L = 20, 50 and 100 Km. It reveals that $P_{in,max}$ decreases exponentially with increasing N at a given value of L.

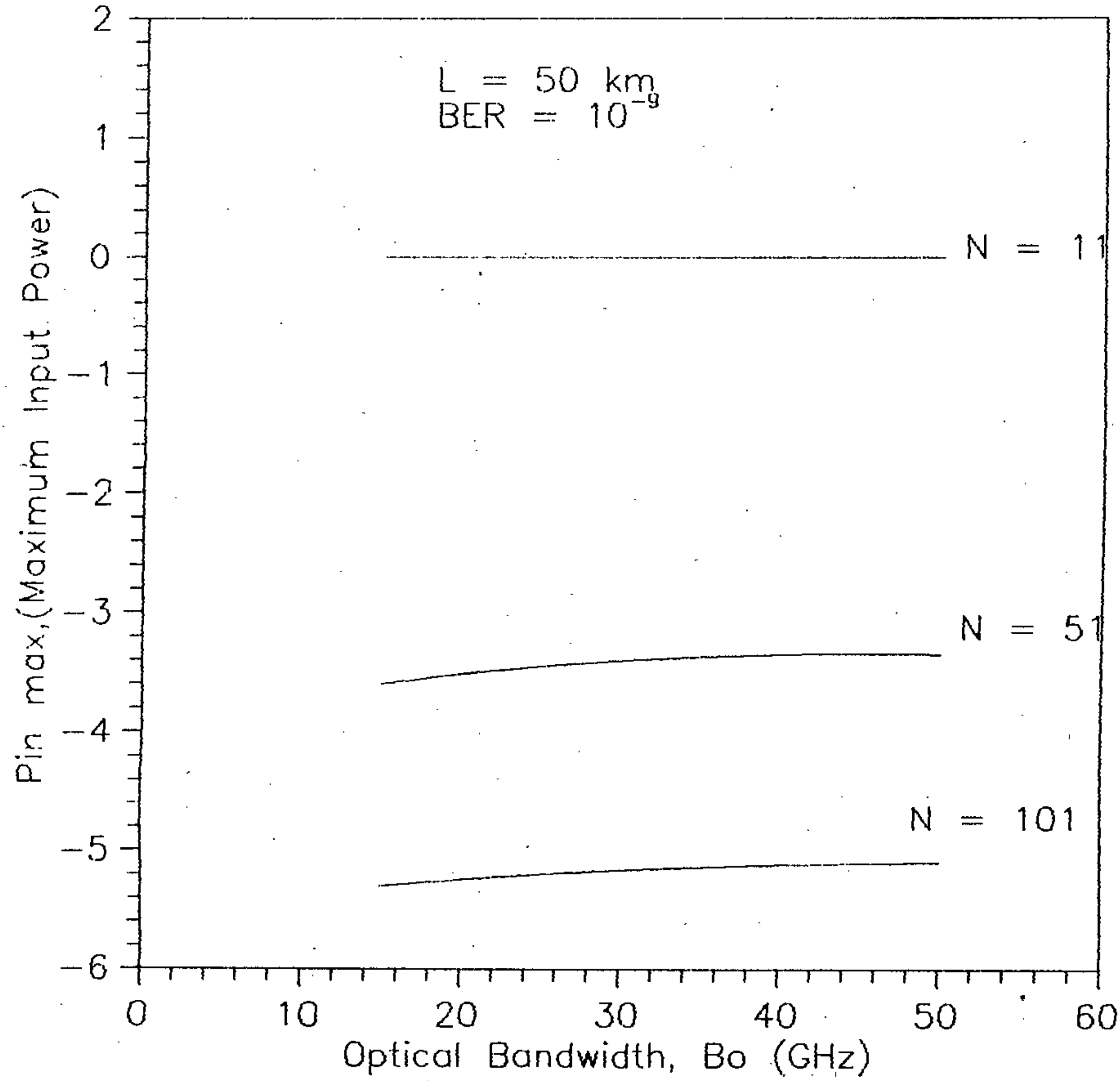

Fig.3.28 Plots of maximum allowable laser transmitter power $P_{in(max)}$ corresponding to the ultimate maximum number of nodes Mmax at BER=10^{-9} versus optical bandwidth B_o (GHz) in the presence of FWM effect when fiber span L=50 Km for the number of WDM channels N=11, 51, 101 and channel separation Δf=25 GHz.

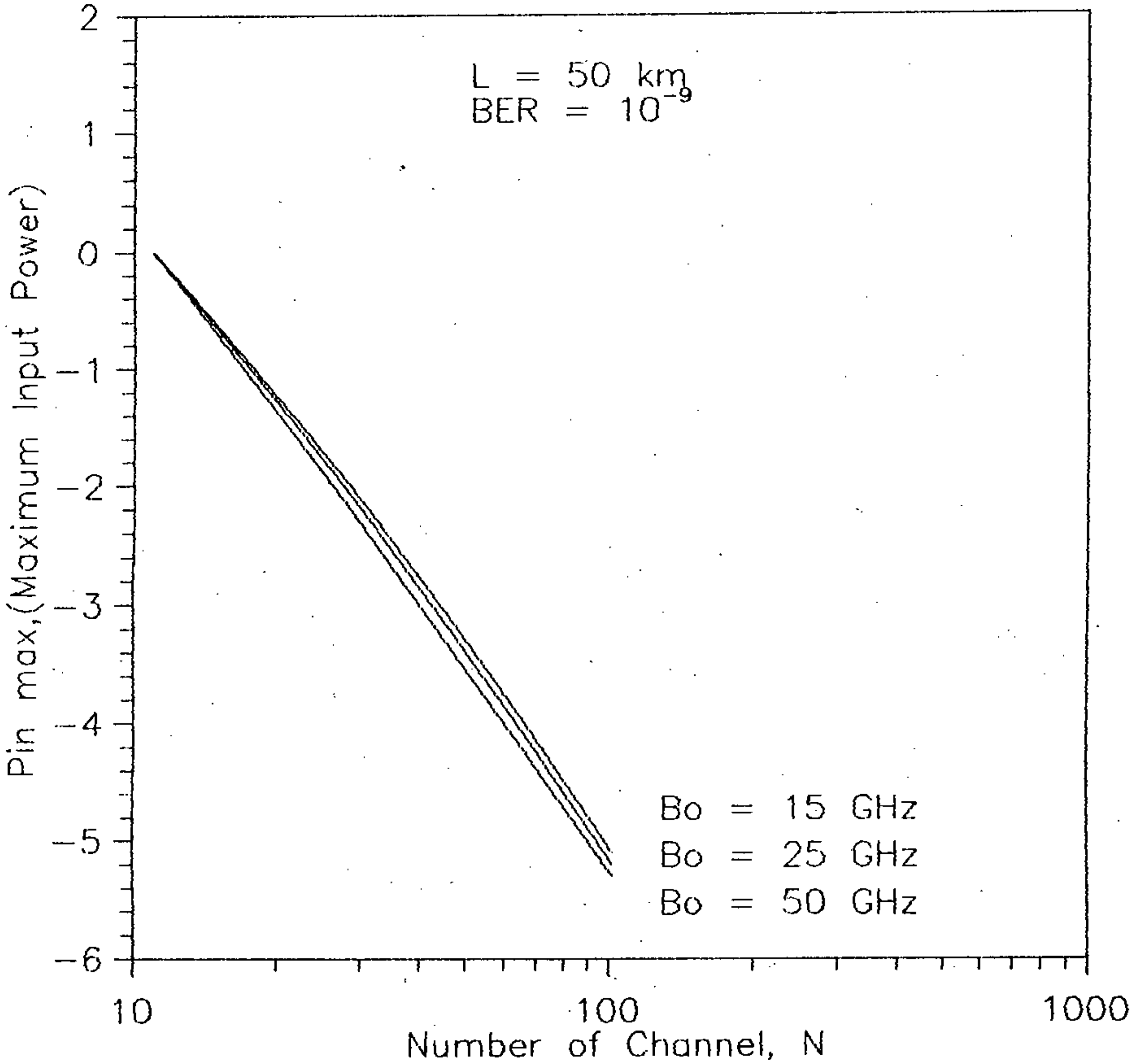

Fig.3.29 Plots of maximum allowable laser transmitter power $P_{in(max)}$ versus number of WDM channels N for three values of optical bandwidth B_o=15, 25, 50 GHz at BER=10^{-9} in the presence of FWM effect and fiber span L=50 Km and channel separation Δf=25 GHz.

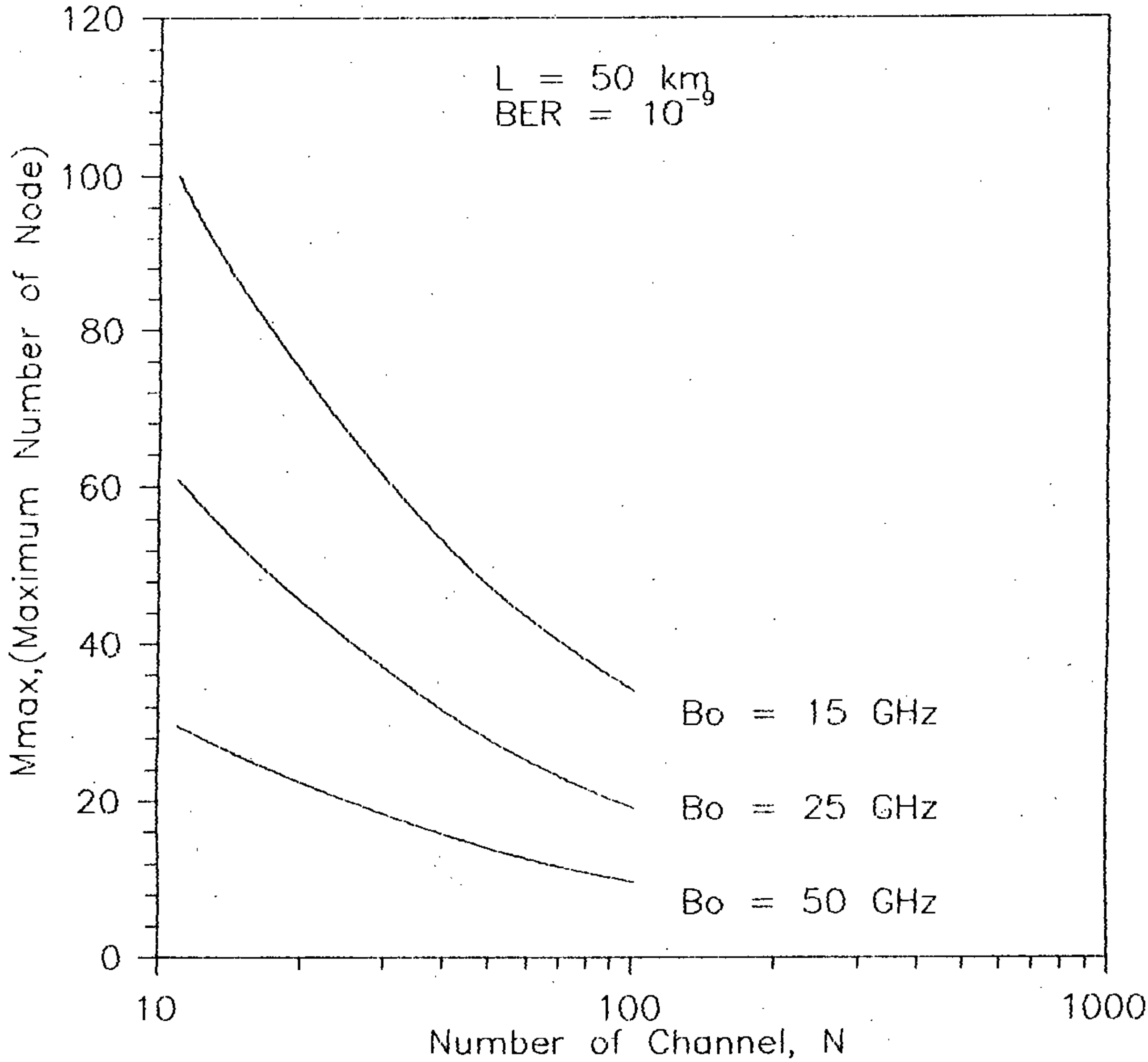

Fig.3.30 Plots of maximum allowable ultimate number of nodes M_{max} versus number of WDM channels N for three values of optical bandwidth B_o=15, 25, 50 GHz at BER=10^{-9} in the presence of FWM effect and fiber span L=50 Km and channel separation Δf=25 GHz.

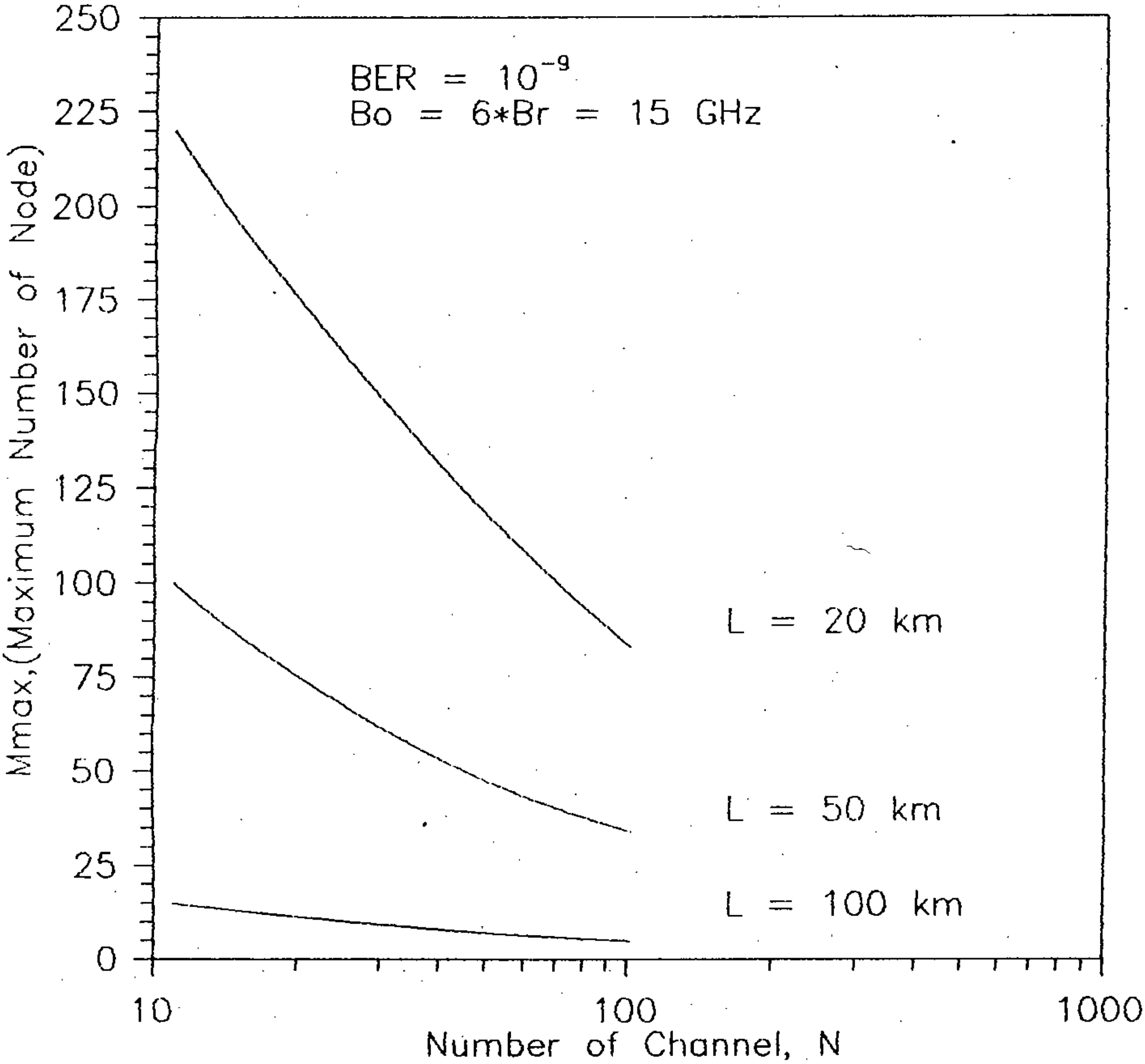

Fig.3.31 Plots of the ultimate maximum number of nodes Mmax, versus number of WDM channels N at BER=10^{-9} for fiber span L=20 Km, 50 Km and 100 Km when optical bandwidth B_o=15 GHz and channel separation Δf=25 GHz.

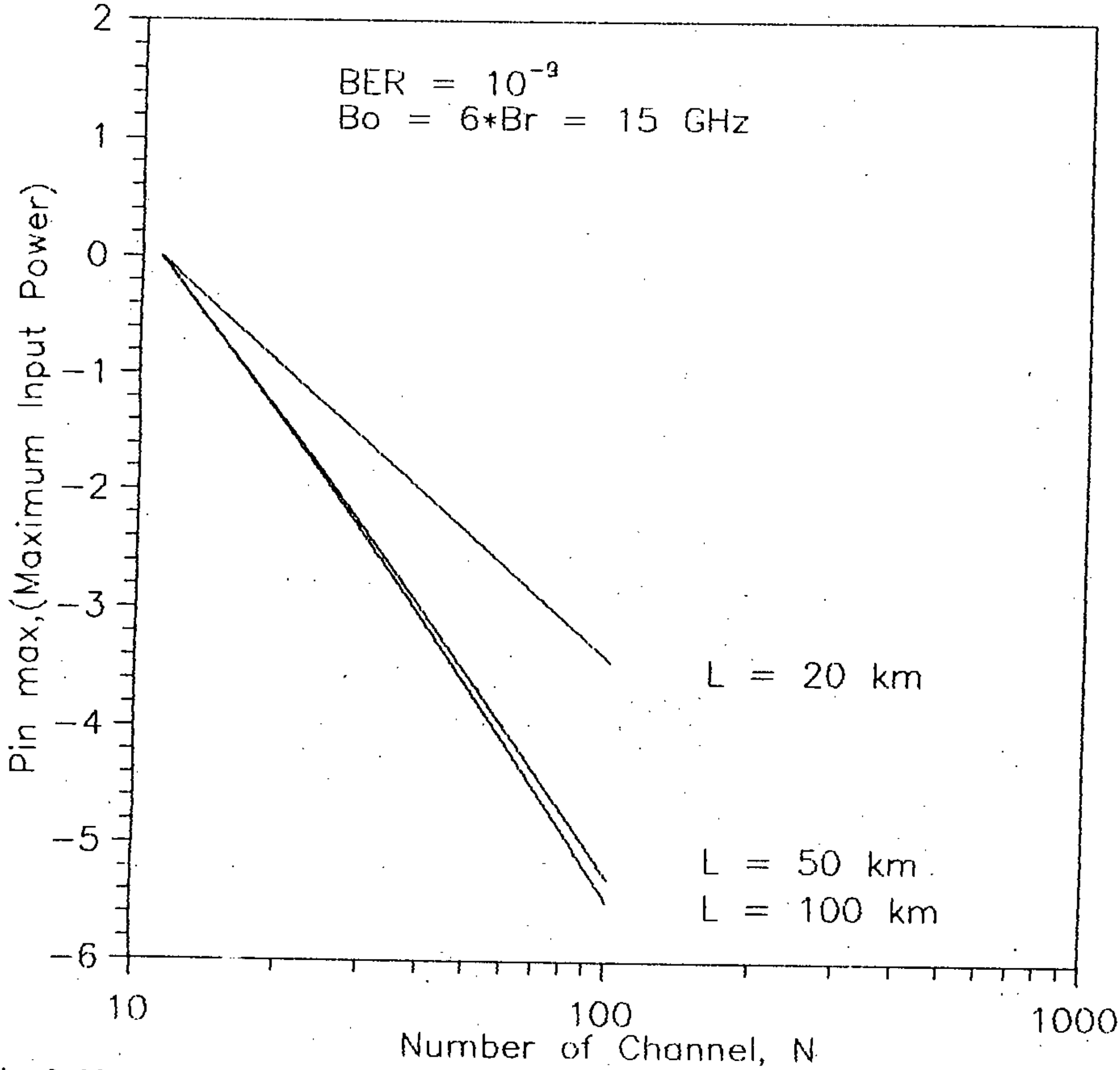

Fig.3.32 Plots of maximum allowable laser transmitter power P_{in} (dBm) corresponding to the ultimate maximum number of nodes Mmax at BER=10^{-9} versus number of WDM channels N for fiber span L=20 Km, 50 Km and 100 Km when optical bandwidth B_o=15 GHz and channel separation Δf=25 GHz.

CHAPTER - IV

CONCLUSIONS AND SUGGESTIONS

4.1 Conclusions:

A detailed theoretical analysis is carried out to evaluate the impact of fiber non-linear effects viz. four-wave mixing (FWM) and chromatic dispersion on the performance of optical multiwavelength transmission system with in-line optical amplifier's and CPFSK heterodyne delay-demodulation reception. Performance results are evaluated at a bit rate of 2.5 Gb/s, considering monomode fiber at an wavelength of 1550 nm for several sets of receiver and system parameters. The results indicate that the bit error rate (BER) increases with increasing value of the number of nodes due to accumulation of optical amplifier's spontaneous emission (ASE) noise for one node to another. At a BER of 10^{-9}, the allowable number of nodes are found to be more at higher input power. However, when the fiber span is larger, the allowable number of nodes is less due to increased ASE with increased amplifier gain to meet additional fiber loss due to increased fiber span.

In the presence of FWM effect the performance of the system is found to be degraded and the number of allowable nodes at BER = 10^{-9} is drastically reduced at a given input transmitter power and fiber span. For example, when the input power P_{in} = 0 dBm and L = 20 Km, N = 11 then the number of allowable node is around 300 whereas it reduces to 220 when the FWM effect is included. The effect of FWM is found to be more pronounced when the number of channels is increased. For example, for P_{in} = 0 dBm, the number of allowable nodes at BER = 10^{-9} is around 220 for N = 11, L = 20 Km whereas it is reduced to 75 and 15 when N is increased to 51 and 101 respectively.

The plots of allowable number of nodes M at BER = 10^{-9} show that the number of nodes increases with P_{in} and attains a maximum value of M_{max} corresponding to a maximum input power $P_{in(max)}$. Further increase in P_{in} causes the number of nodes to decrease. The value of M_{max} depends on the number of channels and fiber span, and decreases with increasing value of the number of channels and fiber span due to increased FWM power and increased ASE and other beat noise components.

Further, it is also observed that the bandwidth of the optical amplifier B_o has a great influence on the maximum achievable number of nodes. At higher optical bandwidth, the influence of FWM and ASE is higher and as a consequence for a given transmitter power P_{in}, the allowable number of channels and/or number of nodes is significantly less. For example, for B_o = 15 GHz and P_{in} = -3.5 dBm, the number of nodes at BER = 10^{-9} is around 60 corresponding to L = 50 Km and N = 11 whereas it reduces to nearly 20 when B_o is increased to 50 GHz. On the other hand, if the number of nodes is kept fixed, the number of channels must be decreased if B_o is increased at a given value of the input power. However, the maximum allowable input power $P_{(inmax)}$ is found to be almost independent of B_o and is significantly less at higher values of N.

It is further noticed that the number of nodes or number of channels can be increased at a given value of P_{in} and fiber span, if the channel separation Δf is increased. It is observed that the number of nodes at a given value of N increases with Δf and attains a maximum value corresponding to an optimum value of the channel separation after which it again decreases. The optimum value of channel separation is slightly less at higher values of input power P_{in}. Also, the required optimum channel separation is slightly higher for increased value of N due to increased FWM effect.

4.2 Suggestions for Future Extension of this Work:

Future works can be carried out to investigate the effect of switch crosstalk in the presence of FWM effect on optically amplified multi-wavelength transport network (MWTN). The packet error probability at a given node can be determined conditioned on a number of bits in a packet. The analysis can be carried out considering a Suffle-Net or a Manhattan Street Network. An upper bound on the network performance in terms of maximum achievable bit rate and throughout for a given packet error rate can be evaluated.

Future work in this area can also be carried out to include the effect of Raman Scattering, the jitter accumulation due to amplifier's spontaneous emission noise, nonuniform chromatic dispersion along the fiber etc.. A detailed Monte-carlo simulation of the wavelength routed optical network can also be carried out to verify the theoretical results and to determine the optimum system parameters for reliable system performance.

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APPENDIX A

The total FWM power can be calculated as follows [8,10,15]:

$$P_F(l) = k^2 . P_{1n}{}^3 \exp(-\alpha l) \sum D_c{}^2 \ \eta_{pqr}$$

$$k^2 = \frac{1024 . \pi^6 . \chi^2 . L_{eff}}{\eta^4 . \lambda^2 . c^2 . A_{eff}}$$

$$\eta_{pqr} = [\frac{\alpha^2}{\alpha^2 + (\Delta\beta)^2}] \, [1 + \frac{4 . \exp(-\alpha l) \sin^2(\Delta\beta l/2)}{[1-\exp(-\alpha l)]^2}]$$

$$x \ \frac{Sin^2(N\Delta\beta l/2)}{Sin^2(\Delta\beta l/2)} \qquad (A.1)$$

$$\Delta\beta = \frac{2\pi D_c . \lambda^2}{c} \ |(f_p - f_r)||(f_q - f_r)|$$

$$\equiv \frac{2\pi D_c . \lambda^2}{c} (\Delta f)^2 (p - r)(q - r)$$

f_i ($i = p$, q, r) = optical frequency of the i-th channel.

χ = nonlinear susceptibility of fiber = 6×10^{-14} m^3/watt-sec.

A_{eff} = effective core area = $2\pi r^2$, r = modified radius, r = W/2

W = modified diameter = 10.7 μm

α = attenuation of fiber = nepers/Km.

Chromatic dispersion coefficient,

D_c = [23 ps/Km nm, λ = 1300] DSF

[1 ps/Km nm, λ = 1550] DSF

D_c = [1 ps/Km nm, λ = 1300] NDF

[17 ps/Km nm, λ = 1550] NDF

value of D = 6 for $p \neq q \neq r$ fully degenerate

= 3 for $p = q \neq r$ partially degenerate

c = velocity of light = 3×10^8 m/s.

P_{in} = Input transmitter power.

$$L_{eff} = \frac{1 - \exp(-\alpha l)}{\alpha} \tag{A.2}$$

where, l = fiber length (Km),

L_{eff} = effective fiber length (Km).

for $l \gg 1$, $L_{eff} = 1/\alpha$.

Δf = frequency separation between two adjacent channels.

λ = wavelength of the signal channel (i.e. the middle channel).

APPENDIX B

At the output of the photodetector,

$$\begin{aligned} r(t) &= R_d\, Re[E(t) + E_{LO}(t)]^2 \\ &= R_d\, Re[\sqrt{2P_s}\exp(j2\pi f_s t + \phi_s' t) \\ &\quad + \sqrt{2P_{pqr}}\exp(j2\pi f_{pqr} t + \theta_{pqr}) \\ &\quad + \sqrt{2P_{Lo}}\exp(j2\pi f_{Lo} t + \theta_{Lo})]^2 \end{aligned} \tag{B.1}$$

where R_d represents the responsivity (A/W) of the PIN photodetector.

The expression of r(t) can be simplified as

$$\begin{aligned} r(t) &= 2\sqrt{2P_s.2P_{pqr}}Cos(2\pi f_s t + \phi_s'(t)).Cos(2\pi f_{pqr} t + \theta_{pqr}) \\ &\quad + 2\sqrt{2P_s.2P_{LO}}Cos(2\pi f_s t + \phi_s'(t)).Cos(2\pi f_{LO} t + \theta_{LO}) \\ &\quad + 2\sqrt{2P_{Lo}.2P_{pqr}}Cos(2\pi f_{Lo} t + \theta_{Lo}).Cos(2\pi f_{pqr} t + \theta_{pqr}) + n'(t) \end{aligned} \tag{B.2}$$

where $n'(t)$ is the additive white noise which includes photodetector shot noise and preamplifier thermal noise.

The above equation can be written in the following form:

$$\begin{aligned} r(t) &= 2R_d\sqrt{P_s.P_{pqr}}Cos[2\pi(f_s - f_{pqr})t + \phi_s'(t) + \theta_{pqr}] \\ &\quad + 2R_d\sqrt{P_s.P_{LO}}Cos[2\pi(f_{LO} - f_s)t + \phi_s'(t) + \theta_{LO}] \\ &\quad + 2R_d\sqrt{P_{LO}.P_{pqr}}Cos[2\pi(f_{LO} - f_{pqr})t + \theta_{LO} + \theta_{pqr}] + n'(t) \end{aligned} \tag{B.3}$$

Assumed that the $(f_s + f_{pqr})$, $(f_s + f_{Lo})$ and $(f_{Lo} + f_{pqr})$ are filtered out, then

$$
\begin{aligned}
r(t) &= 2R_d\sqrt{P_s . P_{LO}}Cos[2\pi f_{IF}t + \phi_s'(t) + \theta_{LO}] \\
&+ 2R_d\sqrt{P_s . P_{pqr}}Cos[2\pi (f_s - f_{pqr})t + \phi_s'(t) + \theta_{pqr}] \\
&+ 2R_d\sqrt{P_{LO} . P_{pqr}}Cos[2\pi (f_{LO} - f_{pqr})t + \theta_{LO} + \theta_{pqr}] + n'(t) \\
&= i_s(t) + i_{LO\text{-}FWM}(t) + i_{s\text{-}FWM}(t) + i_{th}(t) + i_{shot}(t)
\end{aligned}
\tag{B.4}
$$

APPENDIX C

The expressions for the different beat-noise terms are as follows [31]

$$P_{FWM-sp} = 4 I_{FWM} \cdot I_{sp} \cdot \frac{B_e}{B_o} \qquad \text{(C.1)}$$

where B_e = Bandwidth of IF filter,

B_0 = Bandwidth of optical amplifier.

$$\begin{aligned} N_{o\text{-}LOSP} &= 4 R_d^2 P_{LO} \cdot N_o \\ &= 4 R_d P_{LO} \cdot R_d N_o \\ &= 4\,(R_d P_{LO}) \cdot \frac{R_d P_{sp}}{B_o} \qquad \text{(C.2)} \\ &= 4 I_{LO} \cdot \frac{I_{sp}}{B_o} \otimes G_{LO\text{-}PN}(f) \times 2 \end{aligned}$$

where

P_{LO} = Local oscillator power

I_{sp} = Spontaneous emission current

I_{FWM} = Detector current due to FWM power

R_d = Responsivity of photodetector (A/W)

N_0 = Power spectral density of spontaneous emission

N_{sp} = Spontaneous emission factor

G = Gain of optical amplifier

h = Plank's constant

ν = Frequency of optical carrier

$$N_o = N_{sp}(G - 1)h\nu \tag{C.2a}$$

$$\begin{aligned} P_{sp} &= N_o . B_o \\ &= N_{sp}(G - 1)h\nu . B_o \end{aligned} \tag{C.2b}$$

$$I_{sp} = R_d . P_{sp} \tag{C.2c}$$

$$I_{LO} = R_d . P_{Lo} \tag{C.2d}$$

$$I_s = R_d . P_{1n} \tag{C.2e}$$

$$I_{FWM} = R_d . P_{FWM} \tag{C.2f}$$

where

P_{sp} = ASE beat noise power

I_{sp} = Detector current due to P_{sp}

I_{LO} = Detector current due to P_{LO}

I_s = Signal current due to P_{in}

$$\begin{aligned} P_{LOSP} &= N_{o\text{-}LOSP} . B_e \\ &= 4 I_{LO} . I_{sp} . \frac{B_e}{B_o} \otimes G_{LO\text{-}PN}(f) \times 2 \end{aligned} \tag{C.3}$$

where $N_{0\text{-}LOSP}$ = PSD of local oscillator-ASE beat noise

$$N_{o\text{-}ssp} = 4R_d^2\ G\ P_{1n}.N_o$$

$$= 4\,(R_d\ G\ P_{1n})\,R_d\ N_o$$

$$= 4\,(R_d.G_{Is})\,\frac{R_d.P_{sp}}{B_o} \tag{C.4}$$

$$= [4G\ I_s.\frac{I_{sp}}{B_o}]\ \otimes\ G_{FSK\text{-}PN}(f)\times 2$$

where $N_{0\text{-}ssp}$ = PSD of signal-ASE beat noise, $\otimes$ denotes convolution, $G_{LO\text{-}PN}$ (f) = G_{PN}(f - f_{IF}) is phase noise corrupted spectrum of LO signal, $G_{FSK\text{-}PN}$ (f) is the spectrum of phase noise corrupted FSK signal [27],

$$P_{ssp} = [4I_s.I_{sp}\frac{B_e}{B_o}]\ \otimes\ G_{FSK\text{-}PN}(f)\times 2 \tag{C.5}$$

$$
\begin{aligned}
N_{LO\text{-}FWM} &= 4R_d^{\,2}P_{LO}\,.\,N_{FWM} \\
&= 4\,(R_dP_{LO})\,.\,(R_dN_{FWM}) \\
&= 4\,I_{LO}\,.\,\frac{R_d\,.\,P_{FWM}}{B_o} \\
&= [4\,I_{LO}\,.\,\frac{I_{FWM}}{B_o}] \otimes G_{LO\text{-}PN}(f) \times 2
\end{aligned}
\tag{C.6}
$$

where $N_{LO\text{-}FWM}$ = PSD of LO-FWM beat noise

N_{FWM} = PSD of FWM power

$$
\begin{aligned}
P_{LO\text{-}FWM} &= N_{LO\text{-}FWM}\,.\,B_e \\
&= [4\,I_{LO}\,.\,I_{FWM}\,.\,\frac{B_e}{B_o}] \otimes G_{LO\text{-}PN}(f) \times 2
\end{aligned}
\tag{C.7}
$$

$$
\begin{aligned}
N_{s\text{-}FWM} &= 4R_d^{\,2}G\,P_{1n}\,.\,N_{FWM} \\
&= 4\,(R_dP_{1n})\,G\,.\,(R_d\,.\,N_{FWM}) \\
&= 4G\,I_s\,.\,\frac{R_dP_{FWM}}{B_o} \\
&= [4G\,I_s\,.\,\frac{I_{FWM}}{B_o}] \otimes G_{FSK\text{-}PN}(f) \times 2
\end{aligned}
\tag{C.8}
$$

where

N_{s-FWM} = PSD of signal-FWM beat noise

$$P_{s-FWM} = N_{s-FWM} \cdot B_e$$

$$= [4G\, I_s \cdot I_{FWM} \cdot \frac{B_e}{B_o}] \otimes G_{FSK-PN}(f) \times 2 \qquad (C.9)$$

where

P_{s-FWM} = Signal-FWM beat noise power

$$P_{sp-sp} = (\frac{I_{sp}}{B_o})^2 [2B_o - B_e] \cdot B_e \qquad (C.10)$$

where

P_{sp-sp} = ASE-ASE beat noise power.

APPENDIX D

```
C*************** MAIN PROGRAM FOR BER CALCULATION *****************

C      PROGRAM FOR THESIS (PDF CALCULATION) NF2.FOR

C      PROGRAM FOR HET/CPFSK WDM NETWORK NF3.FOR
C      INCLUDING THE EFFECTS OF FWM, SWITCH CROSS_TALK, ASE
       DOUBLE PRECISION Lm_db,Ls_db,Lps_db,Lf_db,Ldm_db,Lsw_db,L_db
       DOUBLE PRECISION Lm,Ls,Lps,Lf,Ldm,Lsw,L,Br,Bo,Delf,Bfp,Be,fin
       DOUBLE PRECISION Lambda,c,nu,h,Nsp1,Nsp2,Pin_dbm,Pin,Pf
       DOUBLE PRECISION G1_db,G2_db,G1,G2,GT,FO,Pase,Is,Iase,Ifwm
       DOUBLE PRECISION kc,Pc,Pspsp,Pssp,Pcsp,Pfwmsp,Pfwm,Ps,Psfwm
       DOUBLE PRECISION Pshot,Ith,Pth,Var1,var0,sigma1,sigma0,Rd
       DOUBLE PRECISION I0,I1,X_db,X,SX,Pir,Pb,Del,Pb1,D,Arg1,Arg2
       DOUBLE PRECISION Pe1,Pe2,BER,e,c1,c2,Pfwm1,Ber1,LT_dB
       DOUBLE PRECISION La,Dc,Aeff,ZF,alpha,alph_db,pi,Err,sign
       DOUBLE PRECISION PST,PE,snr,PY1(1024),PZ1(1024),PEE1(1024)
       DOUBLE PRECISION DELY,YY,PHI,qq,SAI,PDELF,DT,DELNEW,TAO
       DOUBLE PRECISION VAR,Q0,T,Plo,S,BIF,Sigma,U,Z(20),W(20),ILo
       DOUBLE PRECISION FC,FIF,PSPN,PLOPN,PLOSP,PLOFWM,HM,S1,S2,SS,Ic
C      DOUBLE PRECISION PSDFSK,SFWM,FWMSP,BTSSP,FWMLO,INTEGRAL
       Double precision Wlosp,Wssp,Wlofwm,Wfwmsp,Wspsp,Wsfwm,Wcsp

       OPEN(20,file='C:\L3N3FO.DAT')
       OPEN(40,file='C:\POWER.DAT')
       OPEN(40,file='A:\51X1.DAT')
       OPEN(30,file='C:\WATFOR\L3N3FO.DAT')
       OPEN(10,file='C:\WATFOR\WEIGHT.DAT')
C      OPEN(20,file='B:\L3N3FO.DAT')
C      OPEN(10,FILE='B:WEIGHT.DAT')

       DO 11 I=1,10
       READ(10,*)Z(I),W(I)
 11    CONTINUE

C      FRINC=FT
       PI=22.0/7.0
       Rd=0.85
C      Psp=0.002
       Plo=0.001
       ILo=Rd*Plo
       Lm_db=-4.0
       Ls_db=-3.0
       Lps_db=-6.0
C      Lf_db=-9.0
       Ldm_db=-4.0
       Lsw_db=-10.0
```

```
      L_db=0.0
      Alph_dB=0.20

      La=50
C     La=20

      WRITE(20,*)'L=',LA
      WRITE(*,*)'L=',LA
      WRITE(40,*)'L=',LA
      Lf_dB=-alph_dB*La
      Alpha=alph_dB/4.34
      LT_dB=Lm_dB+Ls_dB+Lps_dB+Lf_dB+Ldm_dB+Lsw_dB
      G1_dB=18.0
      G2_dB=-G1_dB-LT_dB
C     WRITE(*,*)'G2_dB=',G2_dB,' Lf_dB=',Lf_dB
      Lm=10.0**(Lm_db/10.)
      Ls=10.**(Ls_db/10.)
      Lps=10.0**(Lps_db/10.)
      Lf=10.0**(Lf_db/10.)
      Ldm=10.0**(Ldm_db/10.)
      Lsw=10.0**(Lsw_db/10.)
      L=10.0**(L_db/10.)

      Br=2.5E9
      T=1.0/BR
      BO=6.0*Br
      Bfp=4.0*Br
      BIF=2.0*Br
      Be=0.7*Br
      DELF = 10*BR
      WRITE(20,*)'Br=',Br,'DELF=',DELF
      lambda=1550.E-9
      c=3.E8
      nu=c/lambda
      h=6.62E-34
      e=1.602E-19

      Xc=0.0
C     WRITE(20,*)'X_=',X
      HM=1.0
      DO 1 ID = 1,1
      DEVN=BR*HM/2.0
      TAO=T/(2.0*HM)
      WRITE(20,*)'Mod Index=',HM ,DEVN
      DT = 0.00
      DO 2 I = 1,1
      WRITE(20,*)'Line width=',DT
```

```
      DELNEW=DT*BR
C     WRITE(*,*)'DELNEW=',DELNEW

      N=51
C     N=101

      WRITE(20,*)'NO OF CHANNELS =',N
      WRITE(30,*)'NO OF CHANNELS =',N
      ITN=10
      Pin_dBm=0.0
      DO 3 IT=1,ITN
      WRITE(*,*)'Pin_dBm=',Pin_dBm
      WRITE(40,*)'Pin_dBm=',Pin_dBm
      Pin=1E-3*10.0**(Pin_dBm/10.)
      G1=10.0**(G1_dB/10.)
      G2=10.0**(G2_dB/10.)
      Pf=Pin*Lsw*Lm*G1
      Dc=1.0E-12*1.E-3*1.E9
      WF=0.5*11.0E-6
      Aeff=2.0*pi*(WF**2)
      an=1.45
      ZF=5.0E-14

      Node=40
      Inc=20
      DO 4 J=1,4
      Node=Node+Inc
      Nsp1=1.5*Node
      Nsp2=1.5*Node

      M=Node
      CALL FWM(Pfwm,La,Lambda,Pf,Dc,an,Aeff,ZF,alpha,N,M,Delf)
C     Pfwm=0.0
C     WRITE(*,*)'Pfwm=',Pfwm
      Pfwm=Pfwm*G2*Lps*Ls*Ldm*Lsw
      Ifwm=Rd*Pfwm

      GT=Lm*Ls*Lf*Lps*Ldm*Lsw*G1*G2
      FO=2.0*Nsp1*(1.0-1./G1)/Lm
      FO=FO+2.0*Nsp2*(1.0-1.0/G2)/(Lm*G1*Ls*Lf*Lps)
      PASE=GT*h*nu*Bo*FO
      Ps=Pin*GT*L*Lsw
      Is=Rd*Ps
      IASE=Rd*PASE*L
C     WRITE(*,*)'Pase=',Pase,'Iase=',Iase
      Fin=(2.0*Delf/Bfp)**2
      Kc=1.0/(1.0+fin)
```

```
      Pc=2.0*kc*GT*Pin*L*Lsw
      Ic=Rd*Pc


c     write(*,*)'Iase=',Iase,' Is=',Is
c     write(*,*)'Ilo=',Ilo,' Ifwm=',Ifwm
c     write(*,*)'Ic=',Ic
C****
      Wfwmsp=4.0*Ifwm*Iase*Be/Bo
      Wlosp=8.0*Ilo*Iase*Be/Bo
      Wssp=8.0*Is*Iase*Be/Bo
      Wcsp=8.0*Ic*Iase*Be/Bo
      Wlofwm=8.0*Ilo*Ifwm*Be/Bo
      Wsfwm=8.0*Is*Ifwm*Be/Bo
      Wspsp=(2.0*Bo-Be)*Be*((Iase/Bo)**2)
c     write(*,*)'Wfwmsp=',Wfwmsp,' Wlosp=',Wlosp
c     write(*,*)'Wssp=',Wssp,' Wlofwm=',Wlofwm
c     write(*,*)'Wsfwm=',Wsfwm,' Wspsp=',Wspsp
C***

C     CALL SPCTRM(NU,T,FC,FIF,DELF,DT,BO,BE,WSSP,PSPN,WLOSP)
      FIF=0.0
      CALL SPCTRM(NU,T,HM,FC,FIF,DELF,DT,BO,BE,PSSP,PSPN,PLOPN,PLOSP
     +,PFWMSP,PSFWM,PLOFWM,PFWM)

      PLOSP=PLOSP*T
      Pssp=Pssp*(T**2.)
      Pfwmsp=Pfwmsp*(T**2)
      Psfwm=Psfwm*(T**3)
      Plofwm=Plofwm*(T**2)
C     WRITE(40,*)'Plosp=',Plosp,' PLOPN=',PLOPN
c     write(*,*)'Pssp=',Pssp
c     WRITE(*,*)'Plosp=',Plosp,' Pfwmsp=',Pfwmsp
c     WRITE(*,*)'Psfwm=',Psfwm,' PLOfwm=', PLOfwm
C     WRITE(40,*)'PFWM=',PFWM,' PLOPN=',PLOPN

      Plosp=Plosp*Wlosp
      Pssp=Pssp*Wssp
      Pfwmsp=Pfwmsp*Wfwmsp
      Psfwm=Psfwm*Wsfwm
      Plofwm=Plofwm*Wlofwm
      Pspsp=1.0*Wspsp
      Pcsp=1.0*Wcsp

c     write(*,*)'Pssp=',Pssp,' Pspsp=',Pspsp
c     WRITE(*,*)'Plosp=',Plosp,' Pfwmsp=',Pfwmsp
c     WRITE(*,*)'Psfwm=',Psfwm,' PLOfwm=', PLOfwm
```

```
c       WRITE(*,*)'Pc=',Pc,' Kc=',Kc
c       write(*,*)'Plofwm=',plofwm
ccc     Pspsp=Bo*Be*((Rd*FO*GT*h*nu*L)**2)
C       Pssp=2.0*FO*h*nu*Pin*Lsw*Be*((Rd*GT*L)**2)
ccc     Pssp=2.0*FO*h*nu*Pin*Lsw*Be*((Rd*GT*L)**2)*Pssp*(T**2)
ccc     Pcsp=2.0*FO*h*nu*GT*Pc*L*Be*(Rd**2)
ccc     Pfwmsp=2.0*(Rd**2)*Pfwm*FO*h*nu*GT*Be*(L**2)
c       Pfwmsp=2.0*(Rd**2)*FO*h*nu*GT*Be*(L**2)*Pfwmsp*(T**3)
ccc     Ps_dbm=10.0*Dlog10(Ps*1.E3)
ccc     Psfwm=4.0*(Rd**2)*Ps*(Pfwm*GT*L)
c       Psfwm=4.0*(Rd**2)*Ps*(Psfwm*GT*L)*(T**4)
        Pshot=2.0*e*Rd*Be*(Pin*Lsw+2.0*kc*Pin*Lsw+Pfwm+h*nu*Bo*FO)*GT*L
C       PLOFWM=0.0

c       Pfwm=Pfwm*G2*Lps*Ls*Ldm*Lsw
ccc     WLOFWM=2*Rd**2*(Pfwm*G2*Lps*Ls*Ldm*Lsw)*Plo/Bo
ccc     WRITE(*,*)'WLOFWM=',WLOFWM
ccc     PLOFWM=WLOFWM*PLOFWM
c       PLOFWM=WLOFWM
C       PLOSP=0.0
ccc     WLOSP=2*Rd**2*Plo*Pase/Bo
C       WRITE(*,*)'WLOSP=',WLOSP,'PLOSP=',PLOSP
ccc     WRITE(*,*)'PLOFWM=',PLOFWM,' PLOSP=',PLOSP
ccc     PLOSP=WLOSP*PLOSP
C       Ith=10 pA/sqrt(Hz) at 2.5 Gb/s
C       Ith=4 pA/sqrt(Hz) at 10 Gb/s

        IF(Br .eq. 2.5E9) ITh=10.0E-12
        IF(Br .eq. 10.E9) Ith=4.0E-12
        SX=Rd*Ps*(Xc**2)
        PTh=(ITh**2)*Be
        var1=Pshot+Pth+Pssp+Pcsp+Pspsp+Pfwmsp+Psfwm+Plofwm+Plosp

C       WRITE(40,*)'Pshot=',Pshot,' Pth=',Pth
C       WRITE(40,*)'Pssp=',Pssp,' Pcsp=',Pcsp
C       WRITE(40,*)'Pspsp=',Pspsp,' Pfwmsp=',Pfwmsp
C       WRITE(40,*)'Psfwm=',PSfwm,' Plofwm=',Plofwm
C       WRITE(40,*)'Plosp=',Plosp,' VAR1=',VAR1

c       WRITE(*,*)'Pshot=',Pshot,' Pth=',Pth
c       WRITE(*,*)'Pssp=',Pssp,' Pcsp=', Pcsp
c       WRITE(*,*)'Pspsp=',Pspsp,' Pfwmsp=',Pfwmsp
c       WRITE(*,*)'Psfwm=',PSfwm,' Plofwm=',Plofwm
c       WRITE(*,*)'Plosp=',Plosp,' VAR1=',VAR1

        Sigma=Sqrt(var1)
```

```
      Pst = 2.0*(Ps+Pfwm) + PASE
      var0=0.5*(2.0*PI*DELNEW*TAO)*(rd*ps)**2
C     WRITE(*,*)'PI=',PI,' DELNEW=',DELNEW
C     WRITE(*,*)'TAO=',TAO,' Rd=',Rd
C     WRITE(*,*)'Ps=',Ps

      VAR = (VAR1+VAR0)
C     WRITE(*,*)'var=',var,' var1=',var1
C     WRITE(*,*)'var0=',var0
      Sigma0=dsqrt(var)

      S1=SQRT(Ps*Plo)
      S2=SQRT(Pfwm*Plo)
      S=2.0*Rd*(S1+S2)
      SS=S*S
C     WRITE(*,*)'S1=',S1,' S2=',S2
C     WRITE(*,*)'S=',S,' SS=',SS
C     WRITE(40,*)'S1=',S1,' S2=',S2
C     WRITE(40,*)'S=',S,' SS=',SS

C     U = ro =snr.
      U = PS/(Pfwm+Pase)
C     U = SS/(2.0*VAR1)
      WRITE(*,*)'U=',U
      WRITE(40,*)'U=',U
      I0 =2.0*RD*PST*GT
C     S=1.0E-5

C     R=No. of Cross-points in each node
      IR=0
      Nd=2**(IR/2)
      CALL BITERR(Delnew,TAO,S,BIF,Sigma,U,BER,Z,W)
      IF( BER .GE. 1.E-15 ) THEN
      WRITE(30,*)Node,sngl(LOG10(BER))
      BER1 = DLOG10(BER*1.E9)
      WRITE(20,*)Node,sngl(BER1)
      WRITE(*,*)'Node=',Node,' Ber=',Ber
      WRITE(40,*)'Node=',Node,' Ber=',Ber
      END IF
C     IF(BER .GT. 1.E-5 ) GO TO 3
 4    CONTINUE
      Pin_dbm=Pin_dbm+5.0
 3    CONTINUE
      DT = DT +0.005
 2    CONTINUE
      HM = HM + 1.0
 1    CONTINUE
```

```
      STOP
      END

C***************** SUBROUTINE 1 *********************************

      SUBROUTINE BITERR(Delnew,TAO,S,BIF,Sigma,U,BER,Z,W)
      DOUBLE PRECISION Delnew,TAO,S,BIF,Sigma,U,BER,Z(20),W(20)

      CALL SIMPX(Delnew,TAO,S,BIF,Sigma,U,BER,Z,W)
C     WRITE(*,*)'BER=',BER
C     PAUSE
      RETURN
      END

C**************** SUBROUTINE 2 ***********************************

      SUBROUTINE PERI(I,IR,Pir)
      DOUBLE PRECISION FactI,FactIR,Factimr,Pir

      CALL Fact1(I,factI)
      CALL Fact1(IR,FactIR)
      IMR=IR-I
      CALL Fact1(Imr,Factimr)
C     WRITE(*,*)'I=',I,'IR=',IR,'IMR=',IMR
      Pir=FactIR*(2.**(-IR))/(FactI*Factimr)
C     WRITE(*,*)'Facti=',facti,'factir=',factir,'factimr=',factimr
C     WRITE(*,*)'Pir=',Pir
      RETURN
      END

C****************** SUBROUTINE 3 ********************************

      SUBROUTINE Fact1(Ind,Fact1A)
      DOUBLE PRECISION Fact1a

      Fact1a=1.0
      IF(Ind .eq. 0) go to 2
      DO 1 J=Ind,1,-1
      Fact1a=Fact1a*Float(J)
C     WRITE(*,*)'J=',J,'FacJ=',Fact1a
    1 CONTINUE
      RETURN
    2 Fact1a=1.0
      RETURN
      END

C ***************** SUBROUTINE 4 *******************************
```

```
      SUBROUTINE SIMPX(Delnew,Tao,S,BIF,Sigma,U,SY,Z,W)

      DOUBLE PRECISION Delnew,Tao,S,BIF,Sigma,U,Z(20),W(20)
      DOUBLE PRECISION S11Y,SY,FUNHY,FUNC,FNINC
      DOUBLE PRECISION SUMKY,FUND,FUNFTY,FUNYK
      DOUBLE PRECISION FUN1HY,FUN1C,FUN1D,F1FSTY,FUN1YK
      DOUBLE PRECISION FUN2HY,FUN2C,FUN2D,F2FSTY,FUN2YK
      DOUBLE PRECISION C,D,DC,DELY,HY,FRSTY,YK,Y(1024)

      PI = 3.141592654D0
      C=0.0
      D =PI/2.0
      DELY = 0.000001
      IMAXY =9
      S11Y=0.0
      SY=0.0
      DC=D-C
      IF(DC) 20,19,20
 19   IERY1=1
      RETURN
 20   IF(DELY) 22,22,23
 22   IERY1=2
      RETURN
 23   IF(IMAXY-1) 24,24,25
 24   IERY1=3
      RETURN
 25   HY=DC/2.0+C
      NHALFY=1
      CALL PDF1(HY,U,FUN1HY)
      CALL GAUSSIAN (HY,FUN2HY,Delnew,Tao,S,BIF,Sigma,Z,W)
      FUNHY=FUN1HY*FUN2HY

C     WRITE(*,*)'HY=',HY,'FUN1HY=',FUN1HY,'f2hy=',fun2hy

      SUMKY=FUNHY*DC*2.0/3.00
      CALL PDF1(C,U,FUN1C)
      CALL GAUSSIAN(C,FUN2C,Delnew,Tao,S,BIF,Sigma,Z,W)
      FUNC=FUN1C*FUN2C

C     WRITE(*,*)'FUNC=',FUNC

      CALL PDF1(D,U,FUN1D)
      CALL GAUSSIAN(D,FUN2D,Delnew,Tao,S,BIF,Sigma,Z,W)
      FUND=FUN1D*FUN2D

C     WRITE(*,*)'FUND=',FUND
```

```
      SY=SUMKY+(FUNC+FUND)*DC/(6.00)
      DO 28 IY=2,IMAXY
      S11Y=SY
      SY=(SY-(SUMKY/2.))/2.0
      NHALFY=NHALFY*2
      ANHLFY=NHALFY
      FRSTY=C+(DC/ANHLFY)/2.0

      CALL PDF1(FRSTY,U,F1FSTY)
      CALL GAUSSIAN(FRSTY,F2FSTY,Delnew,Tao,S,BIF,Sigma,Z,W)
      FUNFTY=F1FSTY*F2FSTY

C     WRITE(*,*)'FUNFTY=',FUNFTY

      SUMKY=FUNFTY
      YK=FRSTY
      KLASTY=NHALFY-1
      FINCY=DC/ANHLFY
      DO 26 KY=1,KLASTY
      YK=YK+FINCY

      CALL PDF1(YK,U,FUN1YK)
      CALL GAUSSIAN(YK,FUN2YK,Delnew,Tao,S,BIF,Sigma,Z,W)
      FUNYK=FUN1YK*FUN2YK
C     WRITE(*,*)'F1YK=',FUN1YK,' F2YK=',FUN2YK
C     WRITE(*,*)'FUNYK=',FUNYK

      SUMKY=SUMKY+FUNYK
 26   CONTINUE
      SUMKY=SUMKY*2.0*DC/(3.*ANHLFY)
      SY=SY+SUMKY

C     WRITE(*,*)'SY=',SY,'S11Y=',S11Y

 27   IF(ABS(SY-S11Y)-ABS(DELY*SY))29,28,28

 28   CONTINUE
      SY=(SY)*2.0
      IERY1=4
      GO TO 30
 29   IERY1=0
C     SY=DABS(SY)*2.0
      SY=(SY)*2.0
C     IF(SY .LE. 1.E-30) SY =0.0
 30   NOY=2*NHALFY
C     WRITE(*,*) 'SY = ',SY
```

```
      RETURN
      END

C****************** SUBROUTINE 5 ********************************

      SUBROUTINE FWM(Pfwm,La,Lambda,Pf,Dc,an,Aeff,Z,alpha,N,M,Delf)
      DOUBLE PRECISION Pfwm,La,Leff,Aeff,pi,Z,Dc,c,alpha,Delf,A3,CN5
      DOUBLE PRECISION A1,A2,lambda,sum,CN1,CN2,CN3,CN4,Eta_ijk,Pf
      DOUBLE PRECISION D

      Leff=(1.0-exp(-alpha*La))/alpha
      PI=22.0/7.0
      C=3.0E8
C     WRITE(*,*)'Pfibre=',Pf,' Leff=',Leff
      A1=1024.0*(pi**6)*((Z*Leff)**2)
      A3=(an**4)*(lambda*c*Aeff)**2
      CK=A1/A3
C     WRITE(*,*)'CK=',CK
      A2=(Pf**3)*(exp(-alpha*La))
C     WRITE(*,*)'A1=',A1,' A2=',A2,' A3=',A3
      SUM=0.0
      Fm=c/lambda
      NH=(N-1)/2
      Fmax=Fm+Delf*NH
      Fmin=Fm-Delf*NH
C     WRITE(*,*)'Fmin=',Fmin,' Fm=',Fm,' Fmax=',Fmax
      term=0
      DO 2 J=0,N
      Fj=Fm+Delf*(J-NH)

C     WRITE(*,*)'Fj=',Fj
      DO 3 K=0,N
      IF(J .EQ. K) go to 3

C     WRITE(*,*)'J=',J,'     K=',K
      Fk=Fm+Delf*(K-NH)
      Fi=Fm-Fj+Fk
      IF(Fi .lt. Fmin) go to 3
      IF(Fi .gt. Fmax) go to 3

      Delf_ik=Abs(Fi-Fk)
      Delf_jk=Abs(Fj-Fk)
C     WRITE(*,*)'Delf_ik=',Delf_ik,' Delf_jk=',Delf_jk
      Delbeta=2.0*Pi*Dc*(lambda**2.)*Delf_ik*Delf_jk/c
C     WRITE(*,*)'alpha=',alpha,' Delbeta=',Delbeta
      Phi=Delbeta*La*1.E3/2.0
      Theta=Sin(Phi)
```

```
C     WRITE(*,*)'Phi=',Phi,' Theta=',Theta

      CN1=(alpha**2)/((alpha*1.E-3)**2+Delbeta**2)
      CN2=4.*exp(-alpha*La)*(Theta**2)
      CN3=(1.0-exp(-alpha*La))**2
      CN5=1.0+CN2/CN3
C     WRITE(*,*)'alph=',alph
C     WRITE(*,*)'CN1=',CN1,' CN5=',CN5
      IF(theta .eq. 0.0) then
      CN4=1.0
      Else
      CN4=(sin(Phi*M)/sin(Phi))**2
      Endif
      Eta_ijk=CN1*CN5*CN4
C     WRITE(*,*)'CN4=',CN4
      IF(Fi .ne. Fk) Then
         IF(Fi .ne. Fj) Then
           D=6.0
           C=3.0/8.0
         Else
           D=3.0
           C=1.0/4.0
         EndIF
         Else
       IF(Fi .ne. Fj) Then
         D=3.0
         C=1.0/4.0
         Else
           D=0.0
           C=1.0/4.0
         EndIF
      EndIF
      term=term+1
      Sum=Sum+(D**2.0)*Eta_ijk
C     WRITE(*,*)'sum=',sum
  3   CONTINUE
  2   CONTINUE
C     WRITE(*,*)'sum=',sum,'term=',term
      Pfwm=A1*A2*sum/A3
C     WRITE(*,*)'Pfwm=',Pfwm
      RETURN
      END

C******************** SUBROUTINE 6 ******************************

      SUBROUTINE PDF1(PHI,U,PDELF)
      DOUBLE PRECISION  PI,H,X1,C,D,U,DELY,SY,PHI,PDELF
```

```
C     DOUBLE PRECISION

      PI = 3.141592654
      C = 0.0
      D = PI
      DELY = 0.001
      IMAXY =9
      CALL  SMP(C,D,DELY,IMAXY,SY,PHI,U)
      PDELF = SY
      RETURN
      END

C******************** SUBROUTINE 7 ********************************

      SUBROUTINE SMP(C,D,DELY,IMAXY,SY,PHI,U)
      DOUBLE PRECISION S11Y,SY,FUN1HY,FUN2HY,FUNHY,FUN1C,FUN2C,FUNC
      DOUBLE PRECISION SUMKY,FUN1D,FUN2D,FUND,F1FSTY,F2FSTY,FUNFTY
      DOUBLE PRECISION FUN1YK,FUN2YK,FUNYK,DCNR,V,U,PHI
      DOUBLE PRECISION C,D,DC,DELY,HY,FRSTY,YK,Y(1024)

      S11Y=0.0
      SY=0.0
      DC=D-C
      IF(DC) 20,19,20
 19   IERY1=1
      RETURN
 20   IF(DELY) 22,22,23
 22   IERY1=2
      RETURN
 23   IF(IMAXY-1) 24,24,25
 24   IERY1=3
      RETURN
 25   HY=DC/2.0+C
      NHALFY=1
      CALL PDF(HY,FUN1HY,PHI,U)
      FUNHY=FUN1HY
      SUMKY=FUNHY*DC*2.0/3.DO
      CALL PDF(C,FUN1C,PHI,U)
      FUNC=FUN1C
      CALL PDF(D,FUN1D,PHI,U)
      FUND=FUN1D
      SY=SUMKY+(FUNC+FUND)*DC/(6.00)
      DO 28 IY=2,IMAXY
      S11Y=SY
      SY=(SY-(SUMKY/2.))/2.0
      NHALFY=NHALFY*2
      ANHLFY=NHALFY
```

```
      FRSTY=C+(DC/ANHLFY)/2.0
      CALL PDF(FRSTY,F1FSTY,PHI,U)
      FUNFTY=F1FSTY
      SUMKY=FUNFTY
      YK=FRSTY
      KLASTY=NHALFY-1
      FINCY=DC/ANHLFY
      DO 26 KY=1,KLASTY
      YK=YK+FINCY
      CALL PDF(YK,FUN1YK,PHI,U)
      FUNYK=FUN1YK
      SUMKY=SUMKY+FUNYK
 26   CONTINUE
      SUMKY=SUMKY*2.0*DC/(3.*ANHLFY)
      SY=SY+SUMKY
 27   IF(ABS(SY-S11Y)-ABS(DELY*SY))29,28,28
 28   CONTINUE
      SY=SY*2.0
      IERY1=4
      GO TO 30
 29   IERY1=0
      SY=SY*2.0
 30   NOY=2*NHALFY
      RETURN
      END

C******************** SUBROUTINE 8 *****************************

      SUBROUTINE PDF(DELF,PFDELF,PHI,U)
      DOUBLE PRECISION PFDELF,PI,C2,C1
      DOUBLE PRECISION DELF,U,PHI,X1

      PI=3.141592654D0
      X1 = EXP(-U)/(4.0*PI)
      C1=EXP(-(U*(SIN(DELF))*(COS(PHI))))
      C2=1+U+ U*(SIN(DELF))*(COS(PHI))
      PFDELF=X1*C1*C2*(SIN(DELF))
C     WRITE(*,*)'DELF=',DELF,'PROB=',PFDELF
      RETURN
      END

C********************** SUBROUTINE 9 *********************************

      SUBROUTINE ERFC(ZZ,YY)
      DOUBLE PRECISION ZZ,YY,P1,P2,Q1,Q2,ERROR,A1,A2,A3,A4,A5,PI,ZABS
      DOUBLE PRECISION ERFZZ,XX
```

```
      PI=3.141592654D0
      ZABS=ABS(ZZ)
      IF(ZZ .eq. 0.0) then
      SIGN=1.0
      ELSE
      SIGN=ZZ/ZABS
      ENDIF
      A1=0.254829592
      A2=-0.284496736
      A3=1.421413741
      A4=-1.453152027
      A5=1.061405429
C     ERROR=1.5E-7
      P1=0.3275911
      P2=1.0/(1.0+P1*ZABS)
      XX=Zabs**2.0
      IF(XX .GT. 700.) Then
      Q1=0.D0
      ELSE
      Q1=DEXP(-1.D0*XX)
      ENDIF
      Q2=A1*P2+A2*(P2**2.)+A3*(P2**3.)+A4*(P2**4.)+A5*(P2**5.)
      ERFZZ=(1.0D0-Q1*Q2)*SIGN
      YY=1.0D0-ERFZZ
C     IF(YY .GT. 1.) WRITE(*,*)'Q1=',Q1,'XX=',XX

C     YY=ERFZZ
      RETURN
      END

C******************** SUBROUTINE 10 ********************************

      SUBROUTINE GAUSSIAN (DPHI,PEDPHI,Delnew,Tao,S,BIF,Sigma,Z,W)
      DOUBLE PRECISION Delnew,Tao,S,PEDPHI,DPHI,PI,BIF,Sigma
      DOUBLE PRECISION PE_DTH,D_THETA,Z(20),W(20)

      PI=22.0/7.0
      N=10
C     DO 1 I=1,N
C     READ(10,*) Z(I),W(I)
C     WRITE(50,*) Z(I), W(I)
C   1 CONTINUE


      SUM=0.0
      DO 2 I=1,N
      D_Theta=Z(I)*SQRT(4.0*PI*Delnew*Tao)
```

```
      CALL PROB(PE_DTh,BIF,D_Theta,Tao,Delnew,S,DPHI,Sigma)
      SUM=SUM+PE_DTH*W(I)
    2 CONTINUE

      PEDPHI=SUM*2.0/(SQRT(PI))
      RETURN
      END

C******************** SUBROUTINE 11 *******************************

      SUBROUTINE PROB (PE_DTh,BIF,D_Theta,Tao,Delnew,
     +S,DPHI,Sigma)

      DOUBLE PRECISION SUM,QAB,QBA,SIGMA,A,B,S,Row,PI,BIF,D_THETA
      DOUBLE PRECISION N1,N2,N3,D,PEO,PE1,PE_DTh,DPHI,TAO,DELNEW
      DOUBLE PRECISION A1,B1

      PI=22.0/7.0
      Beq=1.064*BIF
      Row=EXP(-PI*(Beq*Tao)**2)
      K=(1.0+Row)/(1.0-Row)
      AK=Float(K)

      Beta=1.0
      Gaman=Beta*PI/2.0+D_Theta+DPHI
      An1=S
      And=S
      N1=(1.0+K)*(An1**2+And**2)
      N2=4.0*An1*And*SQRT(AK)*SIN(Gaman)
      N3=2.0*(1.0-K)*An1*And*COS(Gaman)
      D=8.0*(Sigma**2)*(1.0+Row)
C     write(*,*)'s=',s,'k=',k,'sigma=',sigma,'gama=',gaman

      A=SQRT((N1+N2+N3)/D)
      A1=A/SQRT(2.0)
      B=SQRT((N1-N2+N3)/D)
      B1=B/SQRT(2.0)
C     write(*,*)'A=',A,' B=',B
C     write(*,*)'A1=',A1,' B1=',B1
C     CALL QFUN(A,B,QAB,QBA)

      PE1=0.5*(1.0-QAB+QBA)
      PEO=0.5*(1.0-QBA+QAB)
      PE_DTh=PE1+PEO
C     WRITE(*,*)'PEO=',PEO,' PE1=',PE1
C     AB=(A-B)/SQRT(2)
C       CALL erfc((a-b)/SQRT(2.0),pe_dth)
```

```
C         CALL erfc(a1-b1,pe_dth)
C         write(*,*)'pe_dth=',pe_dth
C       PAUSE
        RETURN
        END

C******************** SUBROUTINE 12 *************************

        SUBROUTINE QFUN(A,B,QAB,QBA)
        DOUBLE PRECISION A,B,QAB,QBA,X1,X2,Ep,P,C1,C2,D,BI
        C1=A/B
        C2=B/A
        D=A*B
        P=(A**2+B**2)/2.0
C       WRITE(*,*)'P=',P
        Ep=EXP(-P)
C       WRITE(*,*)'Ep=',Ep

        N=30
        SUM1=0.0
        SUM2=0.0
        DO 10 I=0,N
        AI=FLOAT(I)
        CALL Bessel(D,AI,BI)
C       WRITE(*,*)'AB=',D,'BI=',BI,' I=',I
        X1=C1**I
        X2=C2**I
        SUM1=SUM1+X1*BI
        SUM2=SUM2+X2*BI
 10     CONTINUE
        QAB=EP*SUM1
        QBA=EP*SUM2

        WRITE(*,*)'QAB=',QAB,' QBA=',QBA
        RETURN
        END

C********************* SUBROUTINE 13 **********************

        SUBROUTINE BESSEL(XA,AN,BI)
        DOUBLE PRECISION X,XA,BI,XX,Term,FN,Tol,Fk,EX,PI
        DOUBLE PRECISION factn,bbi,abi,X1

C       READ(*,*) XA,AN
        X=XA
        N=AN
C       WRITE(*,*)'an=',an,' N=',N,' X=',X
```

```
      IER=0
      BI=1.0
      WRITE(*,*) 'Value of N and X in Bessel=',N,X
      IF(N-0) 150,15,10
 10   IF(X-0.) 160,20,20
 15   IF(X-0.) 160,17,20
 17   RETURN
 20   Tol=1.E-30
      IF(X-300.) 40,40,30
 30   FN=Float(N)
      IF(X-FN) 40,40,110
 40   XX=X/2.0

      IF(N .LT. 32) then
         FACTN=1.
      ELSE
         FACTN=1.E0
      ENDIF

      IF(N-1) 70,70,50
 50   DO 60 I=2,N
      FI=Float(I)
      FACTN=FACTN*FI
C     WRITE(*,*)'Factn=',Factn,'I=',I
 60   CONTINUE

 70   Term=(XX**N)
      TERM=TERM/FACTN
      WRITE(*,*)'Term=',Term,'XX=',XX,'N=',N
      IF(N .LT. 32) then
         TERM=TERM*1.E-30
      ELSE
         TERM=TERM*1.E-30
      ENDIF

      BI=TERM
      XX=XX*XX
      DO 90 k=1,100
      ABI=BI*TOL
C     WRITE(*,*)'abi=',abi,' Term=',Term
      IF(ABS(TERM)-ABS(BI*TOL)) 100,100,80
 80   FK=Float(K)*Float(N+K)
      TERM=TERM*(XX/FK)
C     write(*,*)'bil=',bi,' term=',term
 90   BI=BI+TERM*1.E30

 100  RETURN
```

```
 110  FN=4.*(N**2)
      XX=1./(8.*X)
      Term=1.E0
      BI=1.0
      DO 130 k=1,50
      bbi=BI*Tol
C     WRITE(*,*)'BI=',BI,'XX=',XX
C     WRITE(*,*)'bbi=',bbi,' Term=',Term
      IF(ABS(TERM)-ABS(TOL*BI)) 140,120,120
 120  FK=Float(((2*K)-1)**2)
      FLTK=Float(K)
C     WRITE(*,*)'FK=',FK,'  FN=',FN
      TERM=TERM*XX*(FK-FN)/FLTK
      WRITE(*,*)'BIG=',BI,' Term=', Term
 130  BI=BI+TERM
C     WRITE(*,*)'BIG=',BIG,'TERM=',TERM
 140  PI=Dble(22.0/7.0)
      X1=X/50.0
      write(*,*)'X1=',X1,' X=',X,'Big=',Bi
      EX=DEXP(X1)
      write(*,*)'Ex=',Ex
      DX=exp(50.0)
      write(*,*)'Dx=',Dx
      BI=BI*DX
      write(*,*)'bi=',bi
      BI=(BI*EX)/(DSQRT(2.*pi*x))
C     WRITE(*,*)'BI=',BI,'k=',k
      Go To 200
 150  IER=1
      Go To 200
 160  IER=2
 200  RETURN
      END

C********************** SUBROUTINE 14 ***************************

      SUBROUTINE BESELM(XA,BFx)
      DOUBLE PRECISION X,BFx,cf0,cf1,cf2,cf3,cf4,cf5,cf6,cf7,cf8
      DOUBLE PRECISION Err,T,XA

      X=XA
      T=X/3.75D0
      IF(X-3.75D0) 10,10,20
 10   cf0=1.D0
      cf1=3.5156229D0*(T*T)
      cf2=1.2067492D0*(T**6.)
      cf3=0.2659732D0*(T**8.)
```

```
      cf4=0.0360768D0*(T**10.)
      cf5=0.0045813D0*(T**12.)
      Err=1.60D-7
      BFx=cf0+cf1+cf2+cf3+cf4+cf5+err
C     WRITE(*,*)'an=0, X=',X,'  BFx=',BFx
      RETURN
 20   cf0=0.39894228D0
      cf1=0.01328592D0/T
      cf2=0.00225319D0/(T**2.0)
      cf3=-0.00157565D0/(T**3.0)
      cf4=0.00916281D0/(T**4.0)
      cf5=-0.02057706D0/(T**5.0)
      cf6=0.02635537D0/(T**6.0)
      cf7=-0.01647633D0/(T**7.0)
      cf8=0.00392377D0/(T**8.0)
      err=1.9D-7
      BFx=cf0+cf1+cf2+cf3+cf4+cf5+cf6+cf7+cf8+Err
      BFx=BFx*Dexp(x)/(Dsqrt(x))
C     WRITE(*,*)'an=0, X=',X,'  BFx=',BFx
      RETURN
      END

C************************* SUBROUTINE 15 ****************************
*
************************* MAIN SUBROUTINE ***************************
*
      SUBROUTINE SPCTRM(NU,T,HM,FC,FIF,DELF,DT,BO,BE,PSSP,PSPN,PLOPN,
     +PLOSP,PFWMSP,PSFWM,PLOFWM,PFWM)
      DOUBLE PRECISION T,FC,DELF,DT,DELNEW,DELTA,BO,BE,F,TS,BET
      DOUBLE PRECISION FS,FT,PSSP,PSPN,PLOPN,PLOSP,GPN,BOT,AFT,NU
      DOUBLE PRECISION PFWMSP,PSFWM,PLOFWM,PFWM,HM,C1,D1,C2,D2,FRINC
      DOUBLE PRECISION XO(1024),YO(1024),X(1024),Y(1024),FIF,FI
      DOUBLE PRECISION X1(1024),Y1(1024),FIF1,PSD,H,SFSK
      DOUBLE PRECISION X2(1024),Y2(1024),X3(1024),Y3(1024)
      DOUBLE PRECISION X4(1024),Y4(1024)

      BOT=BO*T
      BET=BE*T
C     M1=6
      M1=6
      M2=3
      M=M1+M2+1
      NB=2**M1
      NSB=2**M2
      N=2**M
      NH=N/2
      NQ=N/4
```

```
      F=(BO/2.0)/NQ
      TS=1.0/(N*F)
C     TS=T/NSB
C     FS=1.0/TS
C     F=FS/N
      DELNEW=DT/T
      DELTA=2.0*DELF
      FT=F*T
      FRINC=FT
      C1=0.0
      C2=0.0
      D1=BOT/2.0
C     D2=FIF-BOT/2.0
      D2=BOT/2.0
C     WRITE(*,*)'FT=',FT,'T=',T,'BOT=',BOT
      NN=BOT/FT
      DO 1 I=1,NQ+1
      FI=FT*(I-1)
C     WRITE(*,*)'Fi=',Fi
      CALL PSDFSK(HM,SFSK,FI,T)
      X1(I)=SFSK
      Y1(I)=0.0
  1   CONTINUE
C     WRITE(*,*)'FT=',FT,'BOT=',BOT,'NN=',NN
C     Pause
      DO 10 I=1,NQ+1
      FT=F*T*I

      IF(FT .LE. BOT/2.0) THEN
      X0(I)=1.0
      Y0(I)=0.0
      X4(I)=1.0
      Y4(I)=0.0
      ELSE
      X0(I)=0.0
      Y0(I)=0.0
      X4(I)=0.0
      Y4(I)=0.0
      ENDIF
C     WRITE(*,*)I,'X0=',X0(I)
      IF(DT .NE. 0.0) THEN
C     FIF=0.0
      FIF1=0.0
      CALL PSDPN(DELNEW,FT,FIF1,T,GPN)
      X3(I)=GPN
      ELSE
      X3(I)=0.0
```

```
      ENDIF
      Y3(I)=0.0
   10 CONTINUE

      CALL TRANSF(X0,Y0,NSB,TS,M,T)
      CALL TRANSF(X1,Y1,NSB,TS,M,T)
      CALL TRANSF(X3,Y3,NSB,TS,M,T)
      CALL TRANSF(X4,Y4,NSB,TS,M,T)
      IF(DT .EQ. 0.0) GO TO 11
      CALL SPN(X1,Y1,X3,Y3,PSPN,DT,N,M,F)
      CALL LOPN(X4,Y4,X3,Y3,PLOPN,DT,N,M,F)
      GO TO 12
   11 PSPN=0.0
   12 CALL PSDFWM(X1,Y1,X2,Y2,PFWM,N,M,NSB,F,T)
C     CALL FWM(Pfwm,La,Lambda,Pf,Dc,an,Aeff,Z,alpha,N,M,Delf)

      CALL BTSSP(X1,Y1,X0,Y0,C1,D1,FRINC,PSSP,N,M,F)
C     WRITE(*,*)'PSSP=',PSSP
      CALL BTLOSP(X0,Y0,X4,Y4,C2,D2,FRINC,PLOSP,N,M,F)
      CALL BTSFWM(X1,Y1,X2,Y2,C1,D1,FRINC,PSFWM,N,M,F)
C     WRITE(*,*)'PSFWM=',PSFWM
      CALL BTFWMSP(X0,Y0,X2,Y2,C1,D1,FRINC,PFWMSP,N,M,F)
      CALL BTLOFWM(X2,Y2,X4,Y4,C2,D2,FRINC,PLOFWM,N,M,F)

      PSSP=PSSP*BE/BO
      PSPN=PSPN*BE/BO
C     PLOSP=PLOSP*BE/BO
C     WRITE(*,*)'PSSP=',PSSP,'PSPN=',PSPN
      RETURN
      END

C********************* SUBROUTINNE 16 ***************************

      SUBROUTINE SPN(X1,Y1,X3,Y3,PSPN,DT,N,M,F)
      DOUBLE PRECISION X1(1024),Y1(1024),X3(1024),Y3(1024),PSPN
      DOUBLE PRECISION X(1024),Y(1024),F,DT
      DOUBLE PRECISION C1,D1,FRINC

      IF(DT .EQ. 0.0) GO TO 12
      DO 10 I = 1,N
      AA = X1(I)*X3(I)-Y1(I)*Y3(I)
      BB = X1(I)*Y3(I)+Y1(I)*X3(I)
      X1(I) = AA
      Y1(I) = BB
   10 CONTINUE
   12 DO 11 I=1,N
      X(I) = X1(I)
```

```
      Y(I) = -Y1(I)
 11   CONTINUE
      CALL BEAT(X,Y,C1,D1,FRINC,PSPN,N,M,F)
      RETURN
      END

C****************** SUBROUTINE 17 ******************************

      SUBROUTINE LOPN(X4,Y4,X3,Y3,PLOPN,DT,N,M,F)
      DOUBLE PRECISION X4(1024),Y4(1024),X3(1024),Y3(1024),PLOPN
      DOUBLE PRECISION X(1024),Y(1024),F,DT
      DOUBLE PRECISION C1,D1,FRINC

      IF(DT .EQ. 0.0) GO TO 12
      DO 10 I = 1,N
      AA = X4(I)*X3(I)-Y4(I)*Y3(I)
      BB = X4(I)*Y3(I)+Y4(I)*X3(I)
      X4(I) = AA
      Y4(I) = BB
 10   CONTINUE
 12   DO 11 I=1,N
      X(I) = X4(I)
      Y(I) = -Y4(I)
 11   CONTINUE
      CALL BEAT(X,Y,C1,D1,FRINC,PLOPN,N,M,F)
      RETURN
      END

C******************** SUBROUTINE 18 **********************

      SUBROUTINE PSDFWM(X1,Y1,X2,Y2,PFWM,N,M,NSB,F,T)
      DOUBLE PRECISION X1(1024),X2(1024),F,TS,T,FRINC
      DOUBLE PRECISION Y1(1024),Y2(1024),PFWM,C2,D2,PWR

      Br=2.5E9
      BO=6.0*Br
      TS=T/NSB
      NQ=N/4
      DO 1 I=1,NQ+1
      X2(I)=X1(I)
      Y2(I)=Y1(I)
 1    CONTINUE
      CALL TRANSF(X2,Y2,NSB,TS,M,T)
C     TRANSF(X,Y,NSB,TS,M,T)

      DO 2 I=1,N
C     WRITE(*,*)'X2=',X2(I), 'Y2=',Y2(I)
```

```
      X2(i)=X2(I)*1.E-20
      Y2(I)=Y2(I)*1.E-20
      AA=X2(I)**3-3*X2(I)*Y2(I)**2
      BB=3*(X2(I)**2)*Y2(I)-Y2(I)**3
      X2(I)=AA
      Y2(I)=BB
    2 CONTINUE
      CALL DFT(X2,Y2,N,M)
      C2=0.0
      D2=BO*T
      FRINC=F*T
      CALL INTGRN(C2,D2,X2,FRINC,PWR)
C     WRITE(*,*)'PFWM=',PFWM
C     WRITE(40,*)'PFWM=',PFWM
      RETURN
      END

C******************** SUBROUTINE 19 ***********************

      SUBROUTINE BTSSP(X1,Y1,XO,YO,C1,D1,FRINC,PSSP,N,M,F)
      DOUBLE PRECISION X1(1024),Y1(1024),XO(1024),YO(1024)
      DOUBLE PRECISION X(1024),Y(1024),C1,D1,FRINC,PSSP,F

      DO 1 I =1, N
      AA = X1(I)*XO(I)-Y1(I)*YO(I)
      BB = X1(I)*YO(I)+XO(I)*Y1(I)
      X(I)=AA
      Y(I)=-BB
    1 CONTINUE
      CALL BEAT(X,Y,C1,D1,FRINC,PSSP,N,M,F)
      RETURN
      END

C********************* SUBROUTINE 20 ************************

      SUBROUTINE BTLOSP(XO,YO,X3,Y3,C2,D2,FRINC,PLOSP,N,M,F)
      DOUBLE PRECISION XO(1024),YO(1024),X3(1024),Y3(1024)
      DOUBLE PRECISION X(1024),Y(1024),C2,D2,FRINC,PLOSP,F

      DO 1 I =1, N
      AA = XO(I)*X3(I)-YO(I)*Y3(I)
      BB = XO(I)*Y3(I)+YO(I)*X3(I)
      X(I)=AA
      Y(I)=-BB
C     WRITE(*,*)'X=',X(I),' Y=',Y(I)
    1 CONTINUE
      CALL BEAT(X,Y,C2,D2,FRINC,PLOSP,N,M,F)
```

```
      RETURN
      END

C****************** SUBROUTINE 21 ***********************

      SUBROUTINE BEAT(X,Y,C,D,FRINC,PWR,N,M,F)
      DOUBLE PRECISION X(1024),Y(1024),C,D,FRINC,PWR,F

      CALL DFT(X,Y,N,M)
      DO 2 I=1, N
      X(I)=X(I)/(N*F)
      Y(I)=Y(I)/(N*F)
 2    CONTINUE
      CALL INTGRN(C,D,X,FRINC,PWR)
      PWR=DABS(PWR)
      RETURN
      END

C****************** SUBROUTINE 22 ***************************

      SUBROUTINE BTFWMSP(XO,YO,X2,Y2,C1,D1,FRINC,PFWMSP,N,M,F)
      DOUBLE PRECISION XO(1024),YO(1024),X2(1024),Y2(1024)
      DOUBLE PRECISION C1,D1,FRINC,PFWMSP,X(1024),Y(1024),F

      DO 1 I =1, N
      AA = XO(I)*X2(I)-YO(I)*Y2(I)
      BB = XO(I)*Y2(I)+YO(I)*X2(I)
      X(I)=AA
      Y(I)=-BB
 1    CONTINUE
      CALL BEAT(X,Y,C1,D1,FRINC,PFWMSP,N,M,F)
      RETURN
      END

C****************** SUBROUTINE 23 **************************

      SUBROUTINE BTSFWM(X1,Y1,X2,Y2,C1,D1,FRINC,PSFWM,N,M,F)
      DOUBLE PRECISION X1(1024),Y1(1024),X2(1024),Y2(1024)
      DOUBLE PRECISION X(1024),Y(1024),C1,D1,FRINC,PSFWM,F

      DO 1 I =1, N
      AA = X1(I)*X2(I)-Y1(I)*Y2(I)
      BB = X1(I)*Y2(I)+X2(I)*Y1(I)
      X(I)=AA
      Y(I)=-BB
 1    CONTINUE
      CALL BEAT(X,Y,C1,D1,FRINC,PSFWM,N,M,F)
```

```
      RETURN
      END

C******************** SUBROUTINE 24 *****************************

      SUBROUTINE BTLOFWM(X2,Y2,X3,Y3,C2,D2,FRINC,PLOFWM,N,M,F)
      DOUBLE PRECISION X2(1024),Y2(1024),X3(1024),Y3(1024)
      DOUBLE PRECISION X(1024),Y(1024),C2,D2,FRINC,PLOFWM,F

      DO 1 I =1, N
      AA = X2(I)*X3(I)-Y2(I)*Y3(I)
      BB = X2(I)*Y3(I)+X3(I)*Y2(I)
      X(I)=AA
      Y(I)=-BB
 1    CONTINUE
      CALL BEAT(X,Y,C2,D2,FRINC,PLOFWM,N,M,F)
      RETURN
      END
*
**************** SUBROUTINE 25 ***************************
*
      SUBROUTINE PSDPN(DELNEW,FT,FIF,T,GPN)
      DOUBLE PRECISION DELNEW,FT,GPN,PI,CC,CO,C1,FIF,AFT
      DOUBLE PRECISION DENM1,DENM2,DENM,A1,T,DT

      PI=22.0/7.0
      DT=DELNEW*T
      A1=DELNEW*(T**2.)/(2.0*PI)
      GPN=A1/((FT**2.0)+(DT/2.)**2)
      WRITE(*,*)'GPN=',GPN,'FT','=',FT
      RETURN
      END
*
**************** SUBROUTINE 26 **************************
*
      SUBROUTINE TRANSF(X,Y,NSB,TS,M,T)
      DOUBLE PRECISION X(1024),Y(1024),T,TS,FSA,F,AA

      N=2**M
      NQ=N/4
      NH=N/2
C     TS=T/NSB
      FSA=1.0/TS
      F=FSA/N

      DO 2 I=NQ+2,NH+1
      X(I)=0.0
```

```
      Y(I)=0.0
  2   CONTINUE
      INC=1
      DO 4 I=NH+2,N
      J=I-2*INC
      X(I)=X(J)
      Y(I)=Y(J)
      INC=INC+1
C     WRITE(*,*)'X=',X(I),'Y=',Y(I)
  4   CONTINUE
      CALL DFT(X,Y,N,M)
      DO 5 I=1,N
      X(I)=X(I)*F
      Y(I)=Y(I)*F
      AA=(X(I)**2+Y(I)**2)
C     WRITE(*,*)'AA',I,'=',AA
  5   CONTINUE
      RETURN
      END
*
**************** SUBROUTINE 27 **********************
*
      SUBROUTINE DFT(X,Y,N,M)

C     EMA X,Y,AX
      COMPLEX AX(1024),U,W,T
      DOUBLE PRECISION PI,X(1024),Y(1024)
      DO 4 I=1,N
      AX(I)= CMPLX(X(I),Y(I))
 4    CONTINUE
C     N=2**M
      NV2=N/2
      NM1=N-1
      J=1
      DO 7 I=1,NM1
      IF(I .GE. J) GO TO 5
      T=AX(J)
      AX(J)=AX(I)
      AX(I)=T
 5    K=NV2
 6    IF(K .GE. J) GO TO 7
      J=J-K
      K=K/2
      GO TO 6
 7    J=J+K
      PI=3.141592653589793
      DO 20 L=1,M
```

```
      LE=2**L
      LE1=LE/2
      U= CMPLX(1.0,0.0)
      W= CMPLX(COS(PI/LE1),SIN(PI/LE1))
      DO 20 J=1,LE1
      DO 10 I=J,N,LE
      IP=I+LE1
      T=AX(IP)*U
      AX(IP)=AX(I)-T
 10   AX(I)=AX(I)+T
 20   U=U*W
      DO 21 I=1,N
      X(I)=REAL(AX(I))
      Y(I)=AIMAG(AX(I))
 21   CONTINUE
      RETURN
      END
*
**************** SUBROUTINE 28 ***********************
*
      SUBROUTINE INTGRN(C,D,Y,FRINC,PWR)
      DOUBLE PRECISION Y(1024),C,D,DELY,FRINC,PWR

      DELY=0.005
      IMAXY=9
      CALL SMPSNY(C,D,DELY,IMAXY,PWR,Y,FRINC)
C     WRITE(50,*)'OUTPUT POWER=',PWR
      RETURN
      END
*
********************* SUBROUTINE 29 ***********************
*
      SUBROUTINE SMPSNY(C,D,DELY,IMAXY,SY,Y,FNINC)
      DOUBLE PRECISION S11Y,SY,FUNHY,FUNC,FNINC
      DOUBLE PRECISION SUMKY,FUND,FUNFTY,FUNYK,FT
      DOUBLE PRECISION C,D,DC,DELY,HY,FRSTY,YK,Y(1024)

      S11Y=0.0
      SY=0.0
      DC=D-C
      IF(DC) 20,19,20
 19   IERY1=1
      RETURN
 20   IF(DELY) 22,22,23
 22   IERY1=2
      RETURN
 23   IF(IMAXY-1) 24,24,25
```

```
 24   IERY1=3
      RETURN
 25   HY=DC/2.0+C
      NHALFY=1
C     WRITE(*,*) 'HY=',HY,'FNINC=',FNINC
      I=ANINT(HY/FNINC)+1
C     WRITE(*,*) 'I=',I
      FUNHY=Y(I)
      SUMKY=FUNHY*DC*2.0/3.00
      I=ANINT(C/FNINC)+1
C     FUNC=Y(I)
C     WRITE(* ,*)'C=',C,'I=',I,'FNINC=',FNINC
      FUNC=Y(I)
      I=ANINT(D/FNINC)+1
      FUND=Y(I)
C     WRITE(* ,*)'D=',D,'I=',I
      SY=SUMKY+(FUNC+FUND)*DC/(6.00)
C     WRITE(*,*)'SY=',SY,'SUMKY=',SUMKY,'FUNC=',FUNC,'FUND=',FUND
C     WRITE(*,*)'IMAXY=',IMAXY
      DO 28 IY=2,IMAXY
      S11Y=SY
      SY=(SY-(SUMKY/2.))/2.0
      NHALFY=NHALFY*2
      ANHLFY=NHALFY
      FRSTY=C+(DC/ANHLFY)/2.0
      I=ANINT(FRSTY/FNINC)+1
      FUNFTY=Y(I)
      SUMKY=FUNFTY
      YK=FRSTY
C     WRITE(*,*)'FRSTY=',FRSTY,'SUMKY=FUNFTY=',FUNFTY
      KLASTY=NHALFY-1
      FINCY=DC/ANHLFY
      DO 26 KY=1,KLASTY
      YK=YK+FINCY
      I=ANINT(YK/FNINC)+1
      FUNYK=Y(I)
      SUMKY=SUMKY+FUNYK
C     WRITE(*,*)'FUNYK=',FUNYK,'FINCY=',FINCY,'YK=',YK
 26   CONTINUE
      SUMKY=SUMKY*2.0*DC/(3.*ANHLFY)
C     WRITE(*,*)'SUMKY=',SUMKY,'SY=',SY
      SY=SY+SUMKY
C     WRITE(*,*)'SY=',SY,'S11Y=',S11Y
 27   IF(ABS(SY-S11Y)-ABS(DELY*SY))29,28,28
 28   CONTINUE
      SY=SY*2.0
C     WRITE(*,*)'NO OF ITERATION IS MAX=',IMAXY
```

```
      IERY1=4
      GO TO 30
 29   IERY1=0
      SY=SY*2.0
 30   NOY=2*NHALFY
C     WRITE(*,*)'NO OF ITERATION IN Y=',NOY
      RETURN
      END

C******************** SUBROUTINE 30 ***********************

      SUBROUTINE PSD_FSK(FC,FT,DELTA,T,S_FSK)
      DOUBLE PRECISION Ft,Fc,Gama,Delta,Sai,Alpha(2,2),B(2,2)
      DOUBLE PRECISION T,S_FSK,S_norm,A1,A2,Product,SUM
      DOUBLE PRECISION Theta1,Theta2

      Gama=Ft-Fc
      Theta1=Gama+Delta/2.0
      Theta2=Gama-Delta/2.0
      CALL SINC(Theta1,A1)
      CALL SINC(Theta2,A2)
C     WRITE(50,*)'THETA1=',THETA1,'A1=',A1

      SUM=0.0
      DO 12 j=1,2
      DO 13 k=1,2
C     CALL FUNB(j,k,gama,delta,B)
C     CALL FUNA(j,k,A1,A2,fun_aj,fun_ak)
      Product=B(j,k)*fun_aj*fun_ak
      SUM=SUM+Product
  13  CONTINUE
  12  CONTINUE
      S_norm=(A1+A2+sum)/8.0
      S_FSK=S_norm*T
C     WRITE(50,*)'S_FSK=',S_FSK,'FT=',FT
      RETURN
      END

C******************** SUBROUTINE 31 *****************************

      SUBROUTINE Sinc(Theta,Sinc_th)
      DOUBLE PRECISION Theta,Sinc_th

      IF(Theta .EQ. 0.0) Then
      Sinc_th = 1.0
      Else
      D = Sin(Theta)
```

```
      Sinc_th = D/Theta
      ENDIF
      RETURN
      END

C******************** SUBROUTINE 32 ***************************

      SUBROUTINE PSDFSK(H,SFSK,FI,T)
      DOUBLE PRECISION FI,H,SFSK,AN1,AN2
      DOUBLE PRECISION Ih,DEL,OmegaT,T,ThetaP,ThetaM,ANUM,ADOM
      DOUBLE PRECISION D1,D2,PI

      PI=22.0/7.0
      Ih = Anint (h)
      DEL =h - Ih
      OmegaT = 2.0*PI*FI*T
      IF (DEL .EQ. 0.0 ) Then
      AN1 = COS(OmegaT/2.0)
      AN2 = (1.0/(fI-h/(2.0*T))) - (1.0/(fI+h/(2.0)))
      SFSK = (AN1**2.0*AN2)/(8.0*PI*PI*T)
      ELSE

      Theta = PI*h
      ThetaP = (OmegaT + Theta)/2.0
      ThetaM = (OmegaT - Theta)/2.0
      AN1 = T*(Theta**2.0)

      CALL SINC(ThetaP,SincP)
      CALL SINC(ThetaM,SincM)

      ANUM = AN1*(SINCP**2.0)*(SINCM**2.0)
      D1 = COS(Theta)
      D2 = COS(OmegaT)
      DNOM = 1.0 + D1**2.0 - 2.0*D1*D2

      SFSK = ANUM / DNOM

      ENDIF
      RETURN
      END

C*********************** FINISHED **************************
```