Impact of Four Wave Mixing on Manchester Coded ASK Multichannel Optical Communication Systems

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Manchester Coded ASK 다중채널 광통신 시스템의 Four Wave Mixing에 대한 영향

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ABSTRACT

The performance of Manchester-coded ASK optical wavelength division multiplexing(WDM) systems is evaluated taking into account the shot noise and the four wave mixing(FWM) caused by fiber nonlinearities. The result is compared to conventional non-return-to-zero(NRZ) systems for ASK modulation formats. Further, the dynamic range, defined as the ratio of the maximum input power(limited by the FWM), to the minimum input power(limited by receiver sensitivity), is evaluated. For 1.55 μm 16 channel WDM systems, the dynamic range of ASK Manchester coded systems shows a 2.0 dB improvement with respect to the NRZ. This result holds true for both dispersion-shifted fiber and conventional fiber; it has been obtained for 10 GHz channel spacing, 1 Gbps/channel bit rate.

要 約

Manchester-Coded ASK 광 파장 분할 다중화(WDM) 시스템의 성능이 산탄잡음과 광섬유 비선형성에 의해 야기되는 four wave mixing(FWM)을 고려하여 평가된다. 그 결과는 non-return-to zero(NRZ)를 사용한 ASK 변조방식과 비교된다. 더구나, 최대 입력 파우어(FWM에 의해 제한)와 최소 입력 파우어(수신감도에 의해 제한)의 비로서 정의되는 동적범위(dynamic range)가 평가된다. 1.55 μm 16채널 WDM 시스템에 대해 ASK Manchester-Coded 시스템의 동적범위는 NRZ보다 2.0 dB 개선된다. 이 결과는 10 GHz 채널 간격과 1 Gbps/channel 비트율을 갖는 시스템에서 분산-이동(dispersion-shifed) 광섬유와 기존의 광섬유의 경우 같다.

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I. INTRODUCTION

Future multichannel optical transmission systems will utilize the large bandwidth of single mode fibers using wavelength division multiplexing (WDM). The performance of optical WDM systems may be degraded by the nonlinearities of optical fibers[1,2]. One important fiber nonlinearity is four wave mixing(FWM). This effect occurs when two or more optical waves at different wavelengths mix to produce new optical waves at other wavelengths. The new optical waves may lead to crosstalk[3,4].

Several studies of four wave mixing in WDM communication systems have been published[5, 6]. These studies showed that the FWM crosstalk limits the number of channels, the maximum allowed input power per channel and the channel frequency separation. The allowed power per channel, for a given number of channels and a given frequency separation, depends on the fiber dispersion and attenuation. Previous studies took into account FWM only, and neglected other noise sources, such as shot noise. In addition, the bit error rate in previous studies was calculated under the assumption that the entire power of the interference due to FWM falls into the signal bandwidth.

The FWM is a deterministic nonlinear phenomenon, while the information-carrying optical signals are random due to their independent data streams, asynchronous clocks with timing jitter and laser phase noise. Consequently the resulting interference is a random process. The intensity of the FWM interference exhibits maximum and minimum values and its probability density function (pdf) is bounded between them. The limits are well-defined and can be clearly observed for a small number of channels. The combined effect of many FWM interference terms smears the pdf of the voltage at the decision gate. In our theoretical analysis we approximate the combined FWM interference generated by 16 WDM channels by a bandpass Gaussian process at intermediate frequency (IF). The performance of optical Manchester coded WDM systems is evaluated. Our analysis takes into account the shot noise originating from the light detection process and FWM noise resulting from the optical fiber nonlinearity. These two effects limit the transmission distance as follows: the nonlinearity of the optical fiber limits the maximum transmission power, and the shot noise originating from the detection process limits the minimum receiver power. The ratio of the maximum transmitter power launched into the fiber to the minimum receiver power limits the acceptable attenuation and, therefore, the maximum transmission length.

We show that Manchester coding reduces the impact of FWM on WDM systems. The reason is as follows: The power spectral density of the noise, due to FWM, is given by a triple auto-convolution of the modulated channel power spectral density. Manchester code has wider spectral width than NRZ code and the triple auto-convolution of the Manchester codes shows wider spectral width than that of NRZ codes. The much part of the noise that is generated due to the FWM crosstalk of Manchester coded system come out of the filter bandwidth. Our analysis does take into account the spectral distribution of FWM, and so is believed to be more accurate than previous studies.

The rest of this paper is organized as follows. The system block diagram and the FWM are described in Section II. Receiver output signal and noises are described in Section III. Section IV deals with autocorrelation functions for the NRZ and Manchester codes and the signal-to-noise ratio. Bit error rate is evaluated in Section V. Numerical results and discussion are contained in Section VI. Finally, Section VII contains the conclusions of this paper.

II. WAVELENGTH DIVISION MULTIPLEXING SYSTEM AND FOUR WAVE MIXING

The block diagram of an optical WDM system employing Manchester coding is shown in Fig. 1. Encoders are used to convert NRZ data to Manchester-coded data. The matched filter is used as

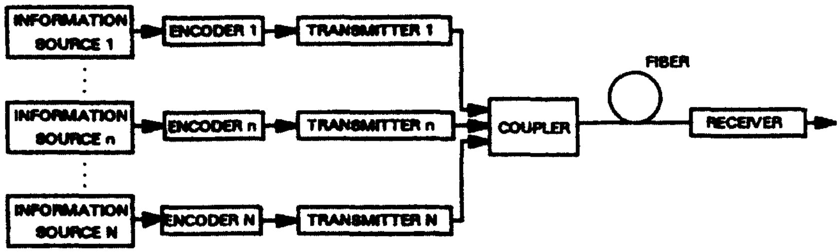

Fig. 1. Block diagram of an optical wavelength division multiplexing system.

a decoder in the receiver. We assume that all transmitters use the same modulation format.

To investigate the impact of FWM on the N-channel optical WDM system, we use the first order nonlinear differential equation that governs the optical wave propagation in nonlinear medium. For the case of light with a finite spectral width, this equation looks as follows [1]:

$$\frac{d}{dz}E_\rho(\omega,z)=-\frac{1}{2}\alpha E_\rho(\omega,z)+\sum_{\mu,\nu} j\frac{2\pi\omega_c}{nc}(D\chi_{1111})\exp(j\Delta kz)\cdot\exp(-\frac{3}{2}\alpha z)\int_{-\infty}^{\infty}d\omega'\int_{-\infty}^{\infty}d\omega'' E^*_{\mu+\nu-\rho}(\omega'+\omega''-\omega)\cdot E_\mu(\omega')\cdot E_\nu(\omega'') \quad (1)$$

where it is assumed that the light propagates along the z axis, E is electric field in the optical fiber, ω is angular light frequency, n is fiber core refractive index, c is the velocity of light in vacuum, α is the fiber power attenuation constant, χ_{1111} is third order nonlinear susceptibility, D is the degeneracy factor, μ, ν and $\rho=1, 2, \cdots$ N and Δk is the phase mismatch given by [2]

$$\Delta k=2\pi\lambda^2C(f_\mu-f_{\mu+\nu-\rho})(f_\nu-f_{\mu+\nu-\rho})/c \quad (2)$$

where C is the group velocity dispersion (G.V.D.). In the derivation of (1), it is assumed that the field depletion due to FWM is small, so that the field amplitude is reduced solely by fiber attenuation. This assumption is valid when the field amplitude of the incident light at the fiber input is much larger than that of the converted wave at the fiber end. Nonlinear term due to four wave mixing is represented by the double convolution of the electric fields of three channels. Expression (1) is a first order nonhomogeneous differential equation. We can obtain the solution at z=L:

$$E_\rho(\omega,L)=u[E_\rho(\omega,0)+\sum_{\mu,\nu} j\frac{2\pi\omega_c}{nc}D\chi_{1111}L_e\cdot\int_{-\infty}^{\infty}d\omega'\int_{-\infty}^{\infty}d\omega'' E^*_{\mu+\nu-\rho}(\omega'+\omega''-\omega)\cdot E_\mu(\omega')\cdot E_\nu(\omega'') \quad (3)$$

where the fiber attenuation u and the effective length in the presence of dispersion L_e are given by

$$u=\exp(-\alpha\cdot L/2) \quad (4)$$

$$L_e=\frac{1-u^2\exp(j\Delta kL)}{\alpha-j\Delta k} \quad (5)$$

Taking the inverse Fourier transform of (3), we obtain the complex amplitude of the electric field in the time domain:

$$E_\rho(t,L)=u'\left\{\sqrt{P_\rho(t)}\exp[j\phi_\rho(t)]+\sum_{\mu,\nu}\sqrt{P_n(t)}\exp[j\phi_n(t)]\right\} \quad (6)$$

where u′ is defined by

$$u'=u/d \quad (7)$$

where d, the conversion factor between power and electric field, is defined by [1]

$$d^2 = \frac{nc}{8\pi} A_{eff} \qquad (8)$$

where A_{eff} is the effective core area of the optical fiber. In equation (6), $P_\rho(t)$ and $\phi_\rho(t)$ are the signal power and phase at the fiber input, and $P_n(t)$ and $\phi_n(t)$ are the pwer and phase of the optical noise process due to FWM given by

$$P_n(t) = \kappa^2 D^2 \eta P_{\mu+\nu-\rho}(t)\, P_\mu(t)\, P_\nu(t) \qquad (9)$$

$$\phi_n(t) = \phi_\mu(t) + \phi_\nu(t) - \phi_{\mu+\nu-\rho}(t) + Arg(L_e) - \frac{\pi}{2} \qquad (10)$$

where the phase mismatch factor η denotes the ratio of the power of the generated waves without phase mathching to their power with phase matching. The parameters κ and η are given by

$$\kappa = \frac{32\pi^3 L_{eff}}{n^2 c \lambda A_{eff}} \chi_{1111} \qquad (11)$$

$$\eta = \frac{\alpha^2}{\alpha^2 + \Delta k^2} \left[1 + \frac{4\exp(-\alpha L)\sin^2(\Delta k L/2)}{\{1-\exp(-\alpha L)\}} \right] \qquad (12)$$

where L_{eff} is the fiber effective length.

Ⅲ. RECEIVER DESCRIPTION

We consider ASK modulation formats in this paper. The block diagram of ASK receiver is shown in Fig. 2. In a multichannel system, complex amplitudes of the received optical signal and local oscillator field are given by [7]

$$E_S = \sum_{\rho=1}^{N} E_\rho(t, L) \qquad \rho = 1, 2, \cdots N \qquad (13)$$

$$E_{LO} = \sqrt{P_{LO}}\,/\,d \qquad (14)$$

where $E_\rho(t, L)$ is the complex amplitude of channel ρ, N is the total number of optical channels, P_{LO} is the local oscillator power, d was defined in expression (8) and E_{LO} is the electric field of the local oscillator. We assume that the channel separation is large enough to neglect the inter-channel crosstalk [7]. The directional coupler output amplitudes are then :

$$E_1(t) = \frac{1}{\sqrt{2}} \left[E_\rho(t, L) + E_{LO} \right] \qquad (15)$$

$$E_2(t) = \frac{1}{\sqrt{2}} \left[E_\rho(t, L) - E_{LO} \right] \qquad (16)$$

The resulting photocurrents are

$$i_1(t) = \frac{R}{2} \{ u^2 P_\rho(t) + u^2 \sum_{\mu,\nu} P_n(t) + P_{LO} + 2u^2 \sum_{\mu,\nu} \sqrt{P_\rho(t) P_n(t)} \cos[\phi_\rho(t) - \phi_n(t)] + 2u^2 \sum_{\mu,\nu} \sum_{\mu' \neq \mu, \nu' \neq \nu} \sqrt{P_n'(t) P_n(t)} \cos[\phi_n'(t) - \phi_n(t)]$$

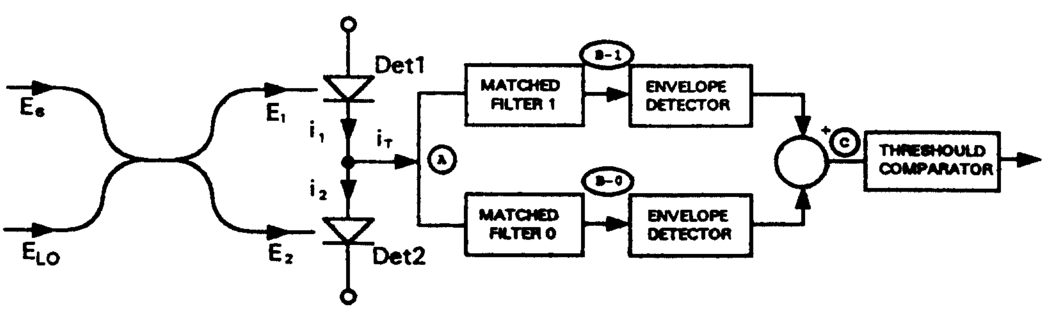

Fig. 2. A Heterodyne ASK Receiver.

$$+2u\sqrt{P_{LO}}\left\{\left[\sqrt{P_\rho(t)}+n_c(t)\right]\cos[\omega_{IF}t+\phi_\rho(t)]\right.$$

$$\left.+n_s(t)\sin[\omega_{IF}t+\phi_\rho(t)]\right\}\}+n_1(t) \quad (17)$$

$$i_2(t)=\frac{R}{2}\{u^2P_\rho(t)+u^2\sum_{\mu,\nu}P_n(t)+P_{LO}$$

$$+2u^2\sum_{\mu,\nu}\sqrt{P_\rho(t)P_n(t)}\cos[\phi_\rho(t)-\phi_n(t)]$$

$$+2u^2\sum_{\mu',\nu'}\sum_{\mu\neq\mu',\nu\neq\nu'}\sqrt{P_n'(t)P_n(t)}\cos[\phi_n'(t)-\phi_n(t)]$$

$$-2u\sqrt{P_{LO}}\left\{\left[\sqrt{P_\rho(t)}+n_c(t)\right]\cos[\omega_{IF}t+\phi_\rho(t)]\right.$$

$$\left.+n_s(t)\sin[\omega_{IF}t+\phi_\rho(t)]\right\}\}+n_2(t) \quad (18)$$

where $P_n(t)$ and $P_n'(t)$ are the noise powers of ρ-th channel corresponding to μ, ν and μ', ν', respectively, R is the photodetector responsivity, $n_1(t)$ and $n_2(t)$ are shot noises originating from the detection process, and the in-phase and the quadrature components of noise are given by

$$n_c(t)=\sum_{\mu,\nu}\sqrt{P_n(t)}\sin\phi_{\mu\nu\rho}(t) \quad (19)$$

$$n_s(t)=\sum_{\mu,\nu}\sqrt{P_n(t)}\cos\phi_{\mu\nu\rho}(t) \quad (20)$$

The phase change due to FWM is given by

$$\phi_{\mu\nu\rho}(t)=\phi_\mu(t)+\phi_\nu(t)-\phi_\rho(t)-\phi_{\mu\nu\rho}(t)+Arg(L_e) \quad (21)$$

The phases $\phi_{\mu\nu\rho}(t)$ are regarded as independent random variables to simplify the analysis. The resulting output voltage is

$$V_T(t)=A\left\{\left[\sqrt{P_\rho(t)}+n_c(t)\right]\cos[\omega_{IF}t+\phi_\rho(t)]\right.$$

$$\left.+n_s(t)\sin[\omega_{IF}t+\phi_\rho(t)]\right\}\}+n_{SH}(t) \quad (22)$$

where the amplitude A and the shot noise $n_{SH}(t)$ are given by

$$A=2Ru\sqrt{P_{LO}} \quad (23)$$

$$n_{SH}(t)=n_1(t)-n_2(t) \quad (24)$$

Ⅳ. CODING METHODS AND SIGNAL-TO-NOISE RATIO

A. Power Spectral Density of Coded Signals

The signal-to-noise ratio for conventional NRZ coded signals and Manchester coded signals are . in this section. In the case of unipolar NRZ, the binary 1 is represented by a higher level (+A) and the binary 0 is represented by a zero level (0). In the Manchester code, the binary 0 is represented by a positive pulse occupying 50% of a bit slot followed by a negative pulse of the same duration. Similarly, a binary 0 is represented by a negative pulse followed by a positive pulse.

The baseband power spectral density (PSD) of a polar NRZ signal is given by [8]

$$G_{NRZ}(f)=T_b\sin c^2(fT_b) \quad (25)$$

where T_b is bit period, and the bit rate is $R_b=1/T_b$; the total signal power is normalized to unity. The autocorrelation function of the baseband NRZ signal is

$$R_{NRZ}(\tau)=\begin{cases}1-\dfrac{|\tau|}{T_b} & |\tau|<T_b\\ 0 & |\tau|>T_b\end{cases} \quad (26)$$

The baseband power spectral density of the Manchester-coded baseband signal is given by [8]

$$G_{MAN}(f)=T_b\sin c^2(fT_b/2)\cdot\sin^2(\pi fT_b/2) \quad (27)$$

The bandwidth of the Manchester-coded signal measured to the first null is twice that of the NRZ bandwidth. The Manchester-coded signal has a zero dc level on the bit by bit basis. Moreover, long strings of zeros do not cause a loss of the clocking signal. The Manchester-coded signal is generated by multiplying frequency-doubled bit clock with the NRZ-coded signal. The autocorrelation function of the Manchester-coded baseband signal is given by

$$R_{MAN}(\tau)=\begin{cases}1-3\frac{|\tau|}{T_b} & |\tau|<\frac{T_b}{2}\\ \frac{|\tau|}{T_b}-1 & \frac{T_b}{2}<|\tau|<T_b\\ 0 & |\tau|>T_b\end{cases} \quad (28)$$

B. Signal-to-Noise Ratio

The matched filter output voltage at the terminal B of Fig. 2 is given by

$$V_O(T_b)=\int_0^{T_b} V_T(t)\cdot h(T_b-t)dt$$
$$=\int_0^{T_b} S(t)\cdot h(T_b-t)dt+\int_0^{T_b} n(t)\cdot h(T_b-t)dt \quad (29)$$

where h(t) is impulse response of the matched filter. The first term gives the signal, and the second term is a zero-mean Gaussian random variable ; its variance is given by

$$\sigma^2=\int_0^{T_b}\int_0^{T_b} R_n(t_1-t_2)\,h(T_b-t_1)\,h(T_b-t_2)dt_1dt_2 \quad (30)$$

where $R_n(t_1-t_2)=E[n(t_1)n(t_2)]$ is the autocorrelation function of the noise.

Assume that all channels use the same modulation scheme and have same power. Then, from expressions (19) and (20), the autocorrelation function of the noise due to FWM is given by

$$R_{n,FWM}(\tau)=\frac{A^2}{2}\,\kappa^2P_p^3\,R'(\tau)\sum_{\mu,\nu}D^2\eta \quad (31)$$

where $R'(\tau)$ is given by

$$R'(\tau)=R^3(\tau)\cos\omega_{IF}\tau \quad (32)$$

where $R(\tau)$ is the autocorrelation function of each signal. An explicit expression for $R(\tau)$ will be given in Section V for each modulation and coding format investigated in this paper. Substituting (31) into (30), we obtain the variance of FWM noise :

$$\sigma_{FWM}^2=\frac{A^2}{2}\,\kappa^2P_p^3V^2S^2T_b^2 \quad (33)$$

where V^2 and S^2 are defined by

$$V^2=\int_0^{T_b}\int_0^{T_b} R'(t_1-t_2)\,h(T_b-t_1)\,h(T_b-t_2)dt_1dt_2 \quad (34)$$

$$S^2=\sum_{\mu,\nu}D^2\eta \quad (35)$$

The autocorrelation function of the shot noise is given by

$$R_{n,SN}(\tau)=qRP_{LO}\,\delta(\tau) \quad (36)$$

Substituting (36) into (30) we obtain the variance of the shot noise :

$$\sigma_{SN}^2=qRP_{LO}W/T_b \quad (37)$$

where W is given by

$$W=T_b\int_0^{T_b} h^2(T_b-t)\,dt \quad (38)$$

Therefore the total signal-to-noise ration γ defined as the ratio of the signal power to the noise power, is given by

$$\gamma=\frac{D^2T_b^2P_p}{\sigma_{FWM}^2+\sigma_{SN}^2}=\frac{1}{\kappa^2P_p^2V^2S^2/2+qW/RT_bu^2P_p} \quad (39)$$

This equation shows that as the input signal power P_p increases, the signal-to-noise ratio γ first increases due to the relative suppression of the shot noise, and then decreases due to the FWM. Thus, at some value of P_p, a peak value of γ is reached corresponding to the optimum system performance.

V. ASK SYSTEM PERFORMANCE EVALUATION

We assume that a matched filter is used in the receiver. The impulse responses of the matched filters for the NRZ and Manchester coded ASK signals are given by

$$h1_{ASK,\,NRZ}(t)=\begin{cases}\frac{2}{T_b}\cos\omega_{IF}t & for\quad t\in[0,\,T_b]\\ 0 & for\quad t\notin[0,\,T_b]\end{cases} \tag{40}$$

$$h0_{ASK,\,NRZ}(t)=\{\ 0 \qquad for\ all\ \mathrm{t} \tag{41}$$

$$h1_{ASK,\,MAN}(t)=\begin{cases}\frac{4}{T_b}\cos\omega_{IF}t & for\quad t\in[T_b/2,\,T_b]\\ 0 & for\quad t\notin[T_b/2,\,T_b]\end{cases} \tag{42}$$

$$h0_{ASK,\,MAN}(t)=\begin{cases}\frac{4}{T_b}\cos\omega_{IF}t & for\quad t\in[0,\,T_b/2]\\ 0 & for\quad t\notin[0,\,T_b/2]\end{cases} \tag{43}$$

where h1 and h0 are impulse response of the matched filter binary 1 and binary 0, respectively. In NRZ coded system, one matched filter is used to detect the data, because the impulse response of the matched filter of the binary 0 is only '0'. In Manchester coded system, two matched filters for the binary 1 and binary 0 are used to detect the data, because binary 1 and binary 0 have same power that is half of the binary 1 of NRZ code. The average signal power per bit for both of the systems is same.

To find the noise variance due to four-wave-mixing, we need the autocorrelation function R (τ) of each ASK signal :

$$R_{ASK,\,NRZ}(\tau)=\frac{1}{4}\,[1+R_{NRZ}(\tau)] \tag{44}$$

$$R_{ASK,\,MAN}(\tau)=\frac{1}{4}\,[1+R_{MAN}(\tau)] \tag{45}$$

where the baseband autocorrelation function $R_{NRZ}(\tau)$ and $R_{MAN}(\tau)$ are given by expressions (26) and (28) respectively. Substituting (44) and (45) into (32), we obtain the autocorrelation function $R'(\tau)$. Next, we substitute (32) and (40) into (34) to obtain

$$V^2_{ASK,\,NRZ}=0.07663 \tag{46}$$

Similarly, substituting (32) and (42) into (34), we obtain

$$V^2_{ASK,\,MAN}=0.06167 \tag{47}$$

Substituting (40) and (42) into (38), we obtain $W_{ASK,\,NRZ}=2$ and $W_{ASK,\,MAN}=4$.

The bit error ratio of the heterodyne ASK system is given by [9]

$$BER_{ASK,\,NRZ}=\frac{1}{2}\,\exp\left[-\frac{\gamma}{8}\right] \tag{48}$$

$$BER_{ASK,\,MAN}=\frac{1}{2}\,\exp\left[-\frac{\gamma}{4}\right] \tag{49}$$

Using expressions (48), (49), (46), (47), (39) and (35), we obtain the numerical value of BER of the ASK multichannel system impaired by the shot noise and the four wave mixing.

Fig. 3 shows a numerical result of BER for the 8 th challel* of a 16 channel WDM system using a dispersion shifted (DS) fiber versus the optical fiber input power for several values of the fiber length. Inspection of Fig. 3 shows that an increase of the input power results in a decrease of the BER for small powers and in an increase of the BER for large input powers. The increase of BER at high powers is due to the FWM that is proportional to the cube of the signal power.

The assumed system parameters are as follows : fiber refractive index 1.47 for non-dispersion shifted fiber (NDS) and 1.476 for DS fiber, wavelength 1.55 μm, attenuation coefficient 0.25 dB/Km, channel spacing 10 GHz, bit rate 1 Gbit/s,

*Other channels have better BER.

effective core area 86.6 μm^2 for NDS fiber and 51.5 μm^2 for DS fiber and group velocity dispersion 17 ps/Km·nm for NDS and 1 ps/Km·nm for DS.

The system dynamic range is defined as the ratio of the maximum input power to minimum input power to maintain BER below 10^{-9}; a more detailed description is contained in Section VI-A. Fig. 3 shows that the dynamic range of a Manchester-coded system is about 2.0 dB larger than that of an NRZ system. The maximum allowable power for the Manchester-coded system is 2.0 dB larger than that for the NRZ coded system, and receiver sensitivity for the Manchester coded system is same as that for the NRZ system. The maximum transmission distance of a system using the Manchester code is 191 Km, and is about 8 Km longer than that of the NRZ system. Table I compares the maximum transmission length of ASK systems utilizing NRZ and Manchester coding.

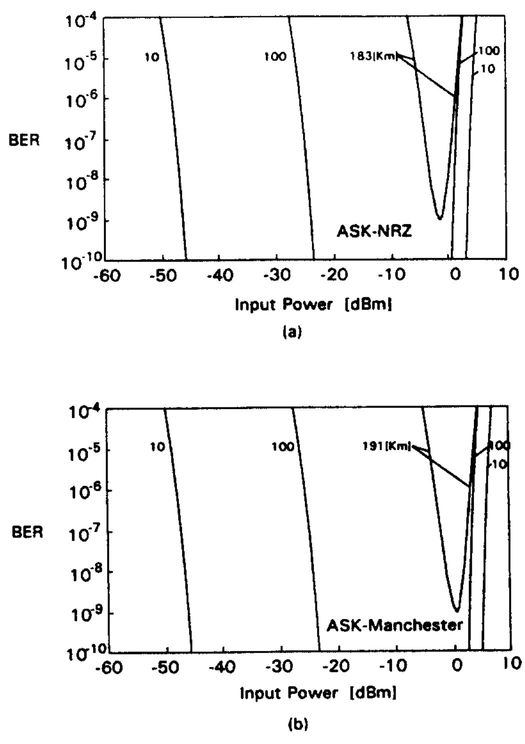

Fig. 3. The bit error rate of a 16 channel ASK coherent WDM system using the DS fiber versus the optical fiber input power; the parameter is the transmission distance. (a) NRZ-coded system, (b) Manchester-coded system.

Table I. Maximum transmission length for a 16 channel WDM system (in Km)

Fiber Type / Coding	DS	NDS
MAN	191	228
NRZ	183	220

VI. NUMERICAL RESULTS AND DISCUSSION

A. Dynamic Range

The fiber input power must be kept between the minimum value P_{min} and the maximum value P_{max} to maintain BER below 10^{-9}. The maximum input power P_{max} is determined by the four wave mixing and the minimum value P_{min} is determined by the shot noise. The computer simulation value of maximum and minimum input powers for 8 th channel of a 16 channels WDM system needed to maintain BER below 10^{-9} are shown in Fig. 4. The upper four curves are the maximum input power for various coding formats and optical fiber types and the lower two curves are the minimum input power for the same coding methods and fiber types. The ratio of the maximum power to the minimum power is defined as the dynamic range, and is an important factor in system design. For example, the dynamic range of a Manchester-coded ASK system with 1 Gbps bit rate and 100 Km non-dispersion sifted fiber is 38 dB, as shown in Fig.4.

Fig. 5 shows the dynamic range of a 16-channel WDM system versus the length of optical fiber for two fiber types and various modulation and coding formats. The curves show that short-distance systems have a large dynamic range of some 70 dB but as the transmission distance increases, the dynamic range decreases, and falls to some 30 dB at 100 Km. Manchester-coded ASK 100 Km systems have some 2.0 dB larger dynamic ranges than corresponding NRZ systems.

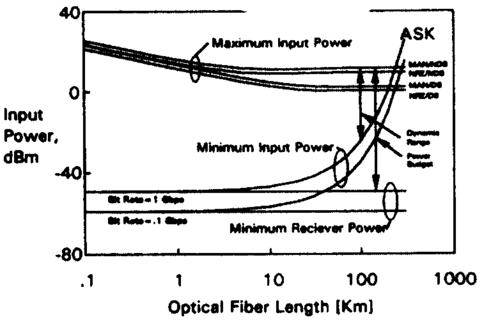

Fig. 4. Maximum input power, minimum input power and system dynamic range and system power budget versus optical fiber length for various fibers and coding formats.

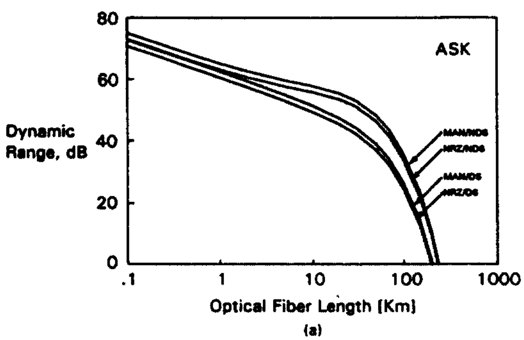

Fig. 5. Dynamic range of a 16 channel WDM system versus optical fiber length for ASK.

B. Power Budget

The power budget is defined as the ratio of the maximum input power to the minimum receiver power needed to keep BER below 10^{-9}. For example, the power budget of Manchester coded ASK system for the 8 th channel of a 16 channels WDM system with 1 Gbps and non-dispersion shifted fiber is about 61 dB and shown in Fig. 4. The drop of the power budget at long lengths is due to the drop of the maximum allowable input power caused by the four wave mixing. For very long fibers, the maximum power level remains almost the same, and therefore, the power budget remains almost the same. The power budgets of ASK systems with various modulation formats and fiber types are given in Table II. Manchester coded systems show about 2.0 dB improvement with respect to NRZ systems. And power budget of systems using NDS fiber is 9.3 dB larger than that of systems using DS fiber.

Table II. Power budget of 100 Km, 16 channel WDM system (in dB)

Fiber Type / Coding	DS	NDS
MAN	51.8	61.1
NRZ	49.8	59.1

C. Polarization Dependence

The strength of crosstalk due to FWM waves is depends on the relative state of polarization of the interacting waves. A parameter $g_{\mu\nu\rho}$ is introduced to take FWM efficiency on the polarization state of lights. The state of polarization of the FWM wave is random comparing that of local oscillator in the optical fiber system without polarization control. A parameter $a_{\rho,\mu\nu\rho}$ is introduced to real part of inner product for polarization state vectors of signal and generated FWM light. In the situation which the polarization states of all channels are completely randomized, $g_{\mu\nu\rho}$ is 1/2 and 3/8 for partially degenerate and the completely nondegenerate channel combinations, respectively [10]. $\langle a_{\rho,\mu\nu\rho}{}^2 \rangle = 1/2$, since the polarization state of generated FWM light is expected to be at random.

In our analysis, we assume the case in which all the interacting waves have random polarizations.

As a result, FWM crosstalk power is decreased to 1/4 and 3/16 of the value expected for a fixed state of polarization for partially degenerate and the completely nondegenerate channel combinations, respectively. The reduction factor are multiplied to expression (33), the variance of FWM crosstalk, for the degenerate and nondegenerate case in the calculation. In this paper, the case of random polarization is considered, so that all our results apply to systems NOT employing polarization-preserving fiber.

Ⅶ. CONCLUSIONS

Wavelength division multiplexing systems are fundamentally limited by the receiver shot noise and by the fiber four wave mixing. In this paper, we analyzed the impact of these limitations on NRZ and Manchester coded ASK systems. The minimum receiver power is determined by the shot noise, and maximum transmitter power is determined by the four wave mixing.

For 1.55 μm dispersion shifted 16 channel ASK systems, having 10 GHz channel spacing and 1 Gbps per channel bit rate, the maximum transmission length is about 183 Km for NRZ and 191 Km for Manchester codes. The maximum transmission length of the ASK system using non-dispersion shifted fiber is 220 Km for NRZ and 228 Km for Manchester codes, respectively. The physical reason is that the transmission length is limited by the FWM rather than by dispersion in this particular case.

To maintain system BER below 10^{-9}, the fiber input power must be kept between the maximum value determined by the fiber four wave mixing and the minimum value determined by the receiver shot noise. The ratio of the maximum input power to the minimum input power is defined as the dynamic range. The dynamic range of 100 Km Manchester coded systems is some 2 dB better than that of NRZ systems for ASK modulation formats.

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