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Effect of Laser Linewidth on the Channel Spacing and Error Rate in Optical Frequency Division Multiplexed Systems Incorporating Semiconductor Optical Amplifier Demultiplexers

R. S. Fyath And Haider M. Al-Sabbagh

Department of Electrical Engineering, College of Engineering,
University of Basrah, Basrah, Iraq

Abstract:

Analysis and performance predictions of optical frequency division multiplexing (OFDM) receivers incorporating semiconductor optical amplifier (SOA) demultiplexer are presented. The analysis takes into account the influence of finite laser linewidth and various noise sources associated with the optically preamplified detection system. The results indicate clearly that the normalized crosstalk level must be kept below -10.8 dB to prevent the occurrence of a bit-error-rate (BER) floor at a level greater than 10^{-9}

تأثير عرض الخط الليزري على المسافة الفاصلة بين القنوات ومعدل الخطأ في نظام الاتصال المتعدد بتقسيم التردد الحاوي على مضخم شبه موصل ضوئي

الملخص:

أجري تحليل للتنبؤ باداء دوائر الاتصال المتعدد بتقسيم التردد (OFDM) الحاوية على مضخم شبه موصل ضوئي. أخذ التحليل بنظر الاعتبار تأثير عرض الخط الليزري المحدد ومصادر الضوضاء المختلفة المرتبطة بنظام الكشف والتضخيم الأولي. تشير النتائج بوضوح أن مستوى الإشارات العابرة المقاييس يجب أن يكون أقل من dB 10.8- لتجنب وصول ثبوتية معدل الخطأ أكثر من 10^{-9}.

1. Introduction

Optical frequency -- division -- multiplexing (OFDM) technique offers a mean of utilizing the vast bandwidth of the single-mode optical fiber to build high – speed communication networks [1-3]. In OFDM, multiple optical channels spaced a part in frequency are used along with tunable optical componenets to provide switchable interconnections between any two ports. Using novel devices such as single-frequency semiconductor lasers and narrowband optical filters, it is now possible to multiplex and demultiplex multi Gbit/s channels with a wavelength spacing of about 1 nm or less [4-6].

There are two channel-selection methods for OFDM signals. One is a direct detection receiver employing a tunable optical filter, such as Fabry-Perot etalons [7, 8]. Optical filters consisting of passive components are relatively inexpensive. The other frequency-selection technique is to use a heterodyne detection receiver employing a tunable laser diode as a local oscillator [9, 10]. Heterodyne detection has higher receiver sensitivity compared with direct detection but it requires a sophisticated laser diode that is characterized by wide tuning range and narrow linewidth.

To enhance the sensitivity of direct detection OFDM receiver, the tunable optical filters can be constructed using narrowband tunable semiconductor optical amplifiers (SOAs). Fabry-Perot, distributed feedback (DFB), and distributed Bragg reflector (DBR) SOAs have been considered for tunable filter applications with encouraging results [11, and reference therein].

The aim of this paper is to examine the performance of direct-detection OFDM receiver incorporating a Fabry-Perot optical amplifier as demultiplexer The effect of crosstalk level and laser linewidth on demultiplexer and receiver characteristics are addressed in details. Expressions have been derived to assess the sensitivity of tunable preamplified receivers in the presence of crosstalk.

2. Demultiplexer characteristics

2.1 Theory

The aim of this section is to investigate the impact of finite laser linewidth on the multiplexing characteristics of a Fabry-Perot (FP) SOA. The performance of a passive single-cavity FP demultiplexers has been addressed by Humblet and Hamdy [12] and Capmany et al. [13] when the employed laser sources have negligible and finite linewidth, respectively. Their results will be extended here for the case under observation by treating the SOA as an active FP filter.

Let the SOA under consideration has a single-cavity FP structure comprising two parallel facets with power reflections R_1 and R_2. The power transfer function of the amplifier is given by [13]:

$$G = \frac{\left\langle |e_o(t)|^2 \right\rangle}{\left\langle |e_i(t)|^2 \right\rangle} \qquad ...(1)$$

where $e_i(t)$ and $e_o(t)$ are the input and output fields and, $\langle \ \rangle$ denotes the ensemble average.

Due to finite laser linewidth, the phase noise associated with the input electric field $e_i(t)$ has double-sided spectral density equal to $\beta/(2\pi f^2)$ rad/Hz. Here β is the full-width at half- maximum (FWHM) linewidth of laser output. The amplified time domain optical field $e_o(t)$ is obtained from the convolution between $e_i(t)$ and the filter (SOA) impulse response. The calculations reveal that the power transfer function of the SOA can be expressed as:

$$G(f,\beta) = k_g(f,\beta)G(f,0) \quad \text{...(2)}$$

where

$$k_g(f,\beta) = \left[\frac{1-(RG_s\Lambda)^2}{1-(RG_s)^2}\right]\left[\frac{(1-RG_s)^2 + 4RG_s\sin^2\theta}{(1-RG_s\Lambda)^2 + 4RG_s\Lambda\sin^2\theta}\right] \quad \text{...(3 a)}$$

$$G(f,0) = G(f,\beta)_{\beta=0} = \frac{(1-R_1)(1-R_2)G_s}{(1-RG_s)^2 + 4RG_s\sin^2\theta} \quad \text{...(3 b)}$$

In eqns. 3 a and 3b, $\Lambda = e^{-\tau/\tau_c}$, $R = \sqrt{R_1R_2}$ and $\theta = \pi\tau f$. Further

G_s = single-pass gain of the optical amplifier

$\tau \equiv 2nL/c_o$ = Cavity round – trip delay

τ_c = Laser coherence time which is proportional to $1/\beta$

L = Cavity length

c_o = Speed of light in vacuum.

n = Refractive index of the SOA active region.

The following remarks are related to eqns. 2 and 3:

i. Equation 3 b is identical to the expression reported in the literature [14] for the optical gain spectrum of FP SOA. Therefore, $G(f,\beta)$ denotes the effective (average) optical gain spectrum of the amplifier.

ii Both $G(f,\beta)$ and $G(f,0)$ achieve maximum and minimum values when $\sin\theta = 0$ and $=1$, respectively. The gain spectrum is periodic with transmission peaks spaced by the free spectral range (FSR) equal to $1/\tau$.

iii. The laser coherence time τ_c is inversely proportional to β, with a proportionality constant equal to 1, π, and 0.664 for rectangular, Lorentzian, and Gausian laser lineshape, respectively [15].

The –3dB pass width B_w of the amplifier can be deduced from eqn.2 as the frequency separation between the points whose gain is equal to half the peak value. The result is:

$$B_w(\beta) = K_\beta B_w(0) \quad \text{...(4)}$$

where

$$k_\beta = \left[\frac{\sqrt{\Lambda}(1-RG_s\Delta)}{(1-RG_s)}\right] \quad \text{...(5 a)}$$

$$B_w(0) = B_w(\beta=0) = \frac{2}{\pi\tau}\sin^{-1}\left[\frac{1-RG_s}{2\sqrt{RG_s}}\right] \quad \text{...(5 b)}$$

To calculate the crosstalk associated with SOA demultiplexing, the following assumptions are assumed:

i. The transmission bandwidth of the OFDM system is equal to one $\text{FSR} = 1/\tau$.

ii. The transmitted channels are equally spaced within the FSR. Therefore, spacing D is given by FSR/M, where M is the number of the multiplied channels.

iii. The channel under observation (0th channel) has a center frequency f_o which is shifted by Δ_o Hz from the peak-gain wavelength of the amplifier.

iv. Worstcase crosstalk is calculated which corresponds to the case where all the other M-1 users are sending "ON" levels.

v. The normalized worstcase crosstalk is computed from

$$S_n = \frac{\sum_{i=1}^{M-1} G(f_i,\beta) - G(f_o,\beta)}{G(f_o,\beta)} \quad ...(6)$$

After mathematical manipulation, the following result is obtained:

$$S_n = \frac{1}{\tau D}\tanh\left(\frac{\pi}{2F}\right)\coth\left(\frac{\pi}{2\tau DF}\right)\frac{1}{1+Q_o^2} - 1$$
...(7)

where

$$Q_o = \frac{2(RG_s\Delta)^{1/2\tau D}}{1-(RG_s\Delta)^{1/\tau D}}\sin(\pi\Delta_o/\tau D) \quad ...(8\ a)$$

and F is the cavity finesse

$$F(\beta) \equiv \frac{FSR}{B_w(\beta)} = \frac{1}{\tau B_w(\beta)} = \frac{F(0)}{k_B} \quad ...(8\ b)$$

where the frequency of the 0th channel, f_o, matches the resonance frequency of the amplifier (i.e, $\Delta_o = 0$), then $Q_o = 0$.

2.2 Simulation Results:

Figures 1 and 2 show, respectively, the constant-bandwidth characteristics of the SOA plotted in the G_o-R and G_o-L planes, respectively. The results are calculated for ideal laser source having negligible linewidth (i.e., $\beta = 0$), and assuming R_1=R_2=R. Here G_o denotes the peak gain of the amplifier in the ideal case of β=0 and it is defined in eqn. 3b with $\sin\theta = 0$. The constant-bandwidth curves are governed by the relations:

$$RG_s = 1 + \sin^2 q_o - 2\sin q_o\left(1+\sin^2 q_o\right)^{1/2} \quad ..(9\ a)$$

$$q_o = \frac{\pi}{2}\frac{\beta_w}{FSR} \quad ...(9\ b)$$

which are deduced from eqn. 5b. The plots in Figs 1 and 2 can be used as a guideline to estimate the SOA parameters (Go, L and R) to achieve the required bandwidth. Table 1 gives the design parameters for amplifier bandwidths of 1 GHz, 5GHz and 10 GHz.

Figure 3 shows the variation of k_g with laser linewidth and assuming R = 0.4 and L=300 μm. Without loss of generality, the laser linewidth is assumed of a rectangular shape. The dashed and broken lines in Fig. 3 denote, respectively, the value of kg associated with maximum and minimum values of amplifier gain. Investigating Fig. 3 reveals that the transmission peaks reduce with β while the transmission minima increase with increasing β.

Table 2 lists the values of k_g and k_B for different values of L, R and G_o. The results indicate clearly that employing a wide linewidth laser leads to lower transmission peaks and wider transmission bandwidth. The effect is more pronounced when R and L are large.

Figure 4 depicts the variation of normalized crosstalk level S_n with normalized channel spacing $D_n \equiv D/B_w(0)$ and for different values of normalized laser linewidth $\beta_n = \beta / B_w(0)$. To suppress the crosstalk level S_n below −10 dB, the normalized channel spacing must be greater than 2.7, 3.5 and 8.5 when $\beta_n = 0$, 1, and 10, respectively. To reduce S_n to less than - 20 dB, the channel spacing D_n must be increased to 7.2, 8.4 and 11.2 where $\beta_n = 0, 1$ and 10, respectively.

3. Receiver Performance

3.1 Theory

A simplified block diagram of an FDM receiver incorporating a SOA demultiplexer is shown in Fig. 5. In the absence of crosstalk, the receiver can be treated as an optically preamplified receiver for a single-channel transmission system and this subject has been addressed carefully in the literature. For example, Olsson [16] has investigated the influence of optical amplifiers on the performance of direct detection receivers under the assumption of a Gaussian statistics for all the noise sources involved in the detection process. Here the analysis of [16] will be extended for a multichannel transmission system.

The signal independent noise is splitted into three components: receiver circuit thermal noise, spontaneous shot noise, and spontaneous-spontaneous beat noise whose variances are denoted by $\sigma^2_{th}, \sigma^2_{sp-sh}$ and σ^2_{sp-sp}, respectively.

The total signal-independent noise variance is given by:

$$\sigma^2 = \sigma^2_{th} + \sigma^2_{sp-sh} + \sigma^2_{sp-sp} \quad \ldots (9a)$$

with

$$\sigma^2_{th} = \frac{4KT}{R_L} F_e B_e$$

$$\sigma^2_{sp-sh} = 2q\Re(G-1)N_{sp}\, hf\, B_e B_o \quad \ldots (9c)$$

$$\sigma^2_{sp-sp} = [\eta q N_{sp}(G-1)]^2 . Be(2B_o - B_e) \quad \ldots (9d)$$

where

K = Boltzmann's constant.

T = Absolute Temperature.

F_e = Excess noise factor of the electronic amplifier.

B_e = Bandwidth of the electrical receiver.

R_L = Electronic amplifier load.

q = Charge of electron.

$\Re$ = Photodiode responsitivity

N_{sp} = Spontaneous emission factor

h = Planck's constant

η = Photodiode quantum efficiency

B_o = Bandwidth of the SOA.

In the absence of crosstalk, the signal-dependent noise is splitted into two components: signal shot noise σ^2_{s-sh} and signal-spontaneous beat noise σ^2_{s-sp}. In this paper we have treated the crosstalk as extra Gaussian noise source whose variance σ^2_c is also signal dependent. Further, the crosstalk-spontaneous beat noise [17] is also included in the analysis. The signal-dependent noise has a variance given by:

$$\sigma^2_s = \sigma^2_{s-sh} + \sigma^2_{s-sp} + \sigma^2_c + \sigma^2_{c-sp} \quad (10\,a)$$

where

$$\sigma^2_{s-sh} = 2q\Re G B_e P \quad \ldots (10\,b)$$

$$\sigma^2_{s-sp} = 4\Re^2 N_{sp}(G-1) hf\, B_e X P \quad \ldots (10\,c)$$

$$\sigma^2_c = \Re^2 S_n^2 G^2 P^2 \quad \ldots (10\,d)$$

$$\sigma^2_{c-sp} = 4\Re^2 N_{sp}(G-1) hf\, B_e\, X\, S_n\, P$$

$$=S_n\sigma^2_{s-sp} \quad \ldots(10\text{ e})$$

In eqn. 10, σ^2_{c-sp} is the variance of crosstalk beat noise, X is an excess noise factor due to FP effects [18], and P is the received optical power when the channel is on the ON-state.

The worstcase crosstalk is considered here by assuming all the other M-1 users are sending ON levels of power p (per user). Equations 9a, 9d, 10b and 10c are quoted from Ref. [16] and included here for the sake of completness.

The bit-error-rate (BER) is calculated using the standard Gaussian approximation [18].

$$BER=\int_Q^{\infty}\frac{\exp(-x^2/2)}{\sqrt{2\pi}}\,dx \quad \ldots(11\text{ a})$$

where

$$Q=\frac{\Re GP}{\sigma_o-\sigma_1} \quad \ldots(11\text{ b})$$

In eqn. 11b, σ_o and σ_1 denote, respectively, the standard deviation of the noise associated with space and mark transmission. Note that $\sigma_o=\sigma$ and $\sigma_1=\sqrt{\sigma^2+\sigma_s^2}$. A BER of 10^{-9} requires Q = 6.

Using eqns. 9 and 10 in eqn. 11 b, the receiver sensitivity $P_{sen}\equiv P/2$ (defined as the average received power required to achieve a specific BER) can be expressed as

$$P_{sen}=\frac{AQ^2N+2Q\left\{A^4\sigma^2+Q^4N^2C-4A^2Q^2\sigma^2C\right\}^{\frac{1}{2}}}{2A\left(A^2-4Q^2C\right)} \quad \ldots(12)$$

where

$$A=\Re G \quad \ldots(13\text{ a})$$

$$C=\Re^2G^2S_n^2 \quad \ldots(13\text{ b})$$

$$N=2q\Re GB_e+4\Re^2XG(G-1)N_{sp}hf(1+S_n) \quad \ldots(13\text{ c})$$

In the absence of crosstalk, eqn. 12 reduces to;

$$P_{seno}=\frac{Q}{2}\left[\frac{N+2AG}{A^2}\right] \quad \ldots(14)$$

The crosstalk power penalty ΔP can be computed in decibels as $10\log\left(\frac{P_{sen}}{P_{seno}}\right)$.

It is worth to notice here that the denominator of eqn. 12 tends to zero when $A^2=4Q^2C$. This indicates the occurrence of a BER-floor and the power penalty ΔP tends to ∞. In this regime the BER is saturated and the receiver performance can not be improved further by increasing the level of the received input signal. In the presence of crosstalk of a level S_n, the BER-floor will occurs at a level correspond to $Q=Q_{floor}$, where Q_{floor} is defined by

$$Q_{floor}=\frac{1}{2S_n} \quad \ldots(15)$$

One can also find that the maximum allowable crosstalk level without introducing a BER-floor at a specific level and it is given by

$$(S_n)_{max}=\frac{1}{2Q} \quad \ldots(16)$$

3.2 Results

Figure 6 shows the variation of the level of BER-floor with normalised worstcase crosstalk S_n. To suppress the BER-floor level below 10^{-9} and 10^{-11}, S_n must be kept below -10.8 dB -11.27 dB, respectively.

Figure 7 shows the dependence of crosstalk induced penalty with normalised channel spacing D_n at a BER = 10^{-9} and taking the normalised laser linewidth β_n as an independent parameter. To suppress the penalty below 1 dB, the channel spacing D_n must be choose greater than 4.54, 5.77, and 10.50 for β_n =0, 1 and 10, respectively. The power penalty increases to 5 dB when the channel spacing reduces to 3.2, 4.13 and 9.17 at β_n =0, 1 and 10 respectively.

Figure 8 shows the sensitivity of a 10 Gbit/s OFDM receiver as a function of normalised channel spacing. The parameter values used in the simulation are: BER = 10^{-9}, λ = 1.55 μm, β = 1 GHz, B_o =10 GHz, B_e= 5GHz, N_{sp}= 1, R = 0.2, G=16.5 dB, η =1, F_e= 3 dB, and R_L = 1 kΩ. The SOA bandwidth and receiver sensitivity in the absence of crosstalk P_{sens} are estimated to be 1 GHz and −39.2 dB, respectively, when ideal laser source with negligible linewidth is employed. However, these results do not change significantly when 1 GHz-linewidth laser is employed since β_n = 0.1 here. Advanced semiconductor laser usually have linewidths below 100 MHz. Thus we expect that finite laser linewidth has negligible effect on OFDM receivers operating at bit rate greater than 1 Gbit/s. It is worth to mention here that the sensitivity of OFDM receiver incorporating passive FP filter (i. e., G=1) is equal to −27 dB under the same condition mentioned above. Thus employing the 16.5 dB-optical amplifier enhances the receiver sensitivity by 12.2 dB in the absence of crosstalk. Figure 8 shows that the sensitivity of the OFDM receiver increases rapidly when the channel spacing reduces to less than 32 GHz.

4. Conclusions

A theoretical analysis has been presented to assess the effect of crosstalk on the performance of multichannel optical frequency division multiplexed transmission systems employed with a semiconductor optical amplifier-based demultiplexer. Analytical expressions have been derived to assess receiver sensitivity under the assumption of Gaussian statistics for noise source and crosstalk. The results indicate clearly that to suppress the crosstalk-induced penalty to less than 1 dB, the normal channel spacing D_n must be chosen greater than 4.54, 5.77 and 10.5 for normalised laser linewidth of 0, 1 and 10, respectively. A bit-error- rate floor occurs at 10^{-9} when the channel spacing D_n reduces to 3.0, 3.9 and 8.9 when β_n = 0, 1 and 10, respectively.

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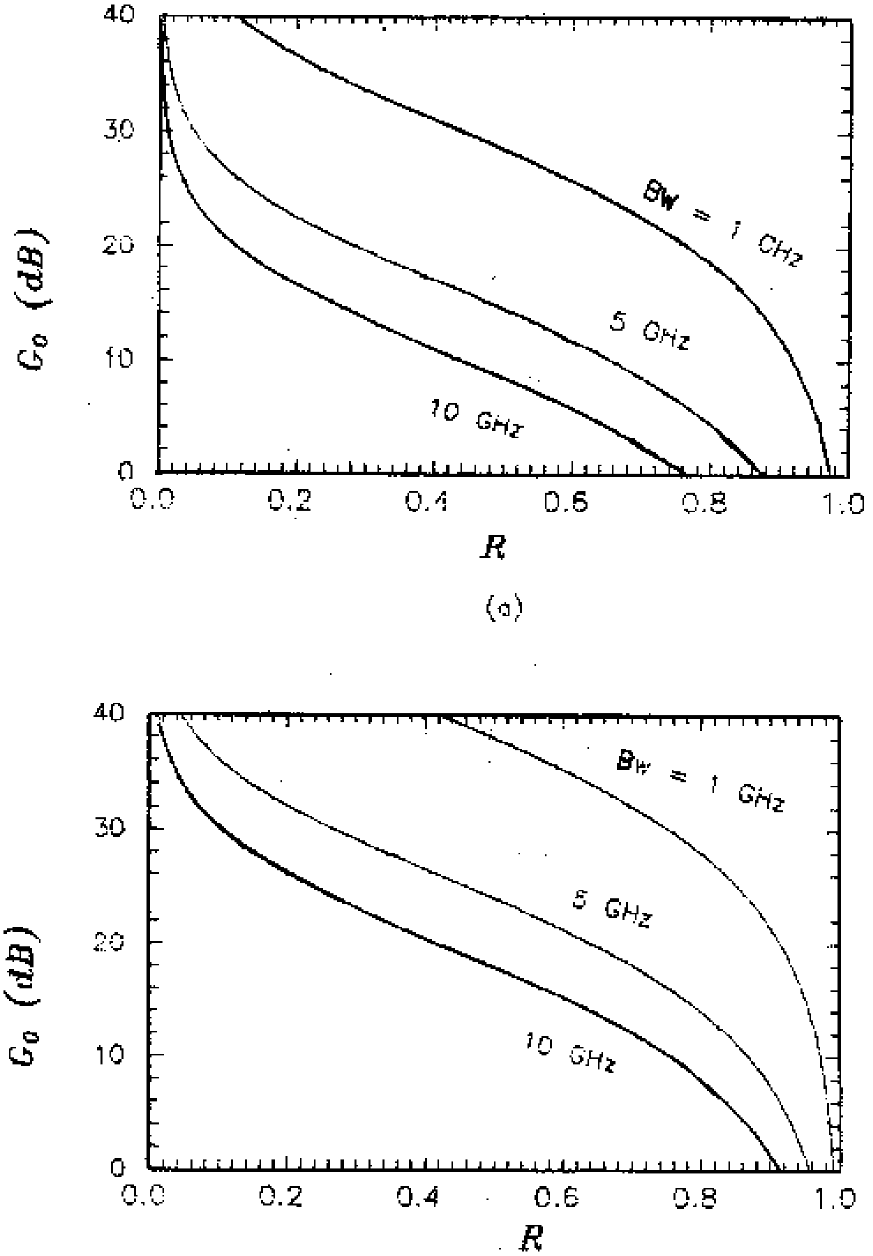
Table (1) Design (structure) parameters for SOA demultiplixer to achieve the required transmission band width.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	1	36.5	31.0	25.7
	5	22.5	17.0	11.7
	10	16.5	11.0	5.7
	1	46.1	40.5	35.3
	5	32.1	25.6	21.3
	10	26.1	20.6	15.3

Table (2) Values of k_g and k_B for different values of G_o, L, R and β.

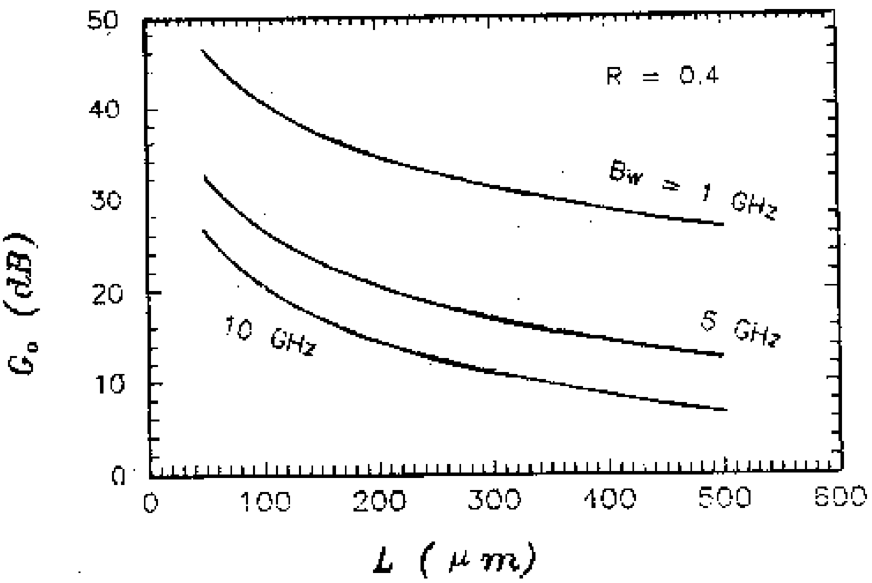
G_o (dB)	L ([illegible])	R	β = [illegible] MHz			β = 1 GHz		
			K_{g1}	K_{g2}	K_B	K_{g1}	K_{g2}	K_B
20	300	0.7	0.98	1.02	1.023	0.808	1.21	1.237
30	300	0.7	0.93	1.07	1.075	0.57	1.71	1.75
30	100	0.7	0.975	1.024	1.025	0.8	1.24	1.25
30	300	0.4	0.972	1.026	1.028	0.78	1.25	1.283

Note: k_{g1} and k_{g2} denote k_g evaluated at gain maximum and minimum, respectively.

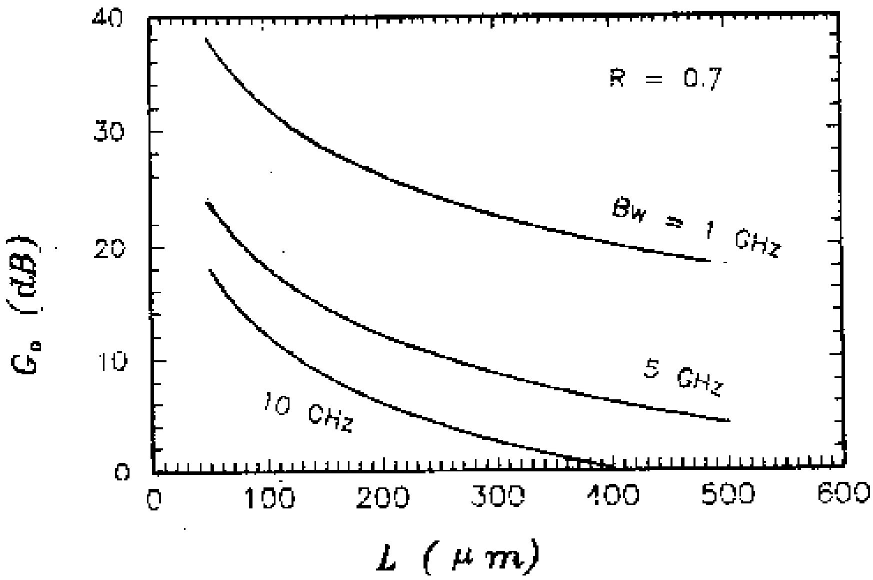


(b)

Fig. 1 Constant-bandwidth characteristics plotted in $G_o - R$ plane (a) L = 300 μm, (b) L = 100 μm.



(a)



(b)

Fig. 2 Constant bandwidth characteristics plotted in G_0 – L plane.
(a) R = 0.4 (b) R = 0.7

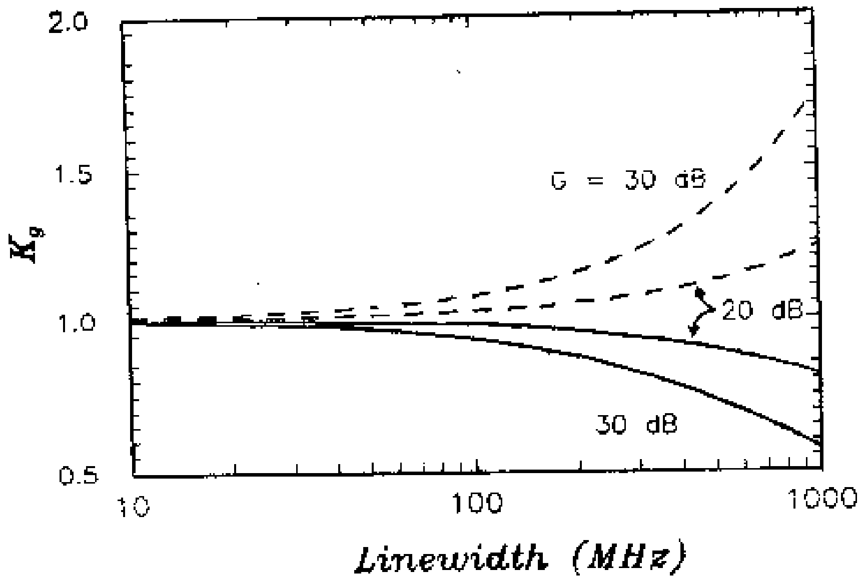


Fig. 3 Variation of the parameter K_g with laser linewidth β

------ K_g at gain maxima, ——— K_g at gain minima.

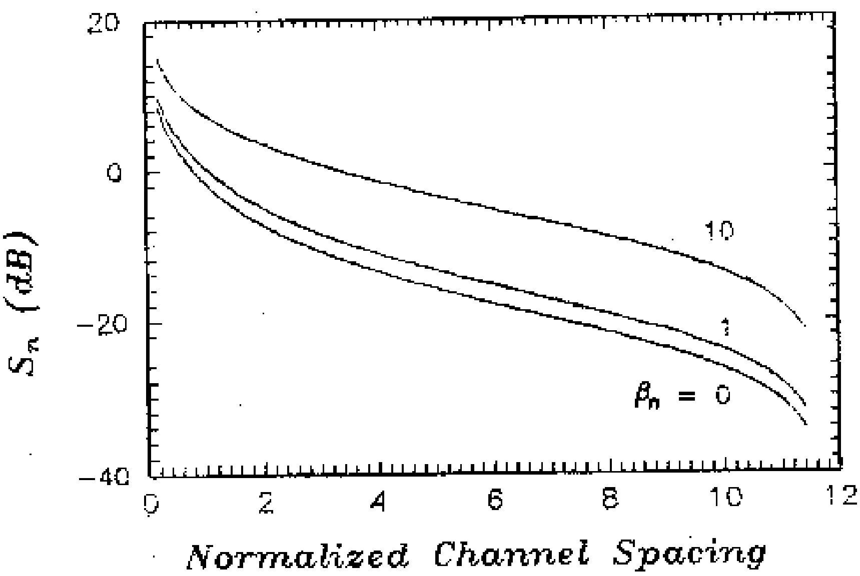


Fig. 4 Crosstalk level S_n as a function of normalized channel spacing, for different values of normalized laser linewidth β_n.

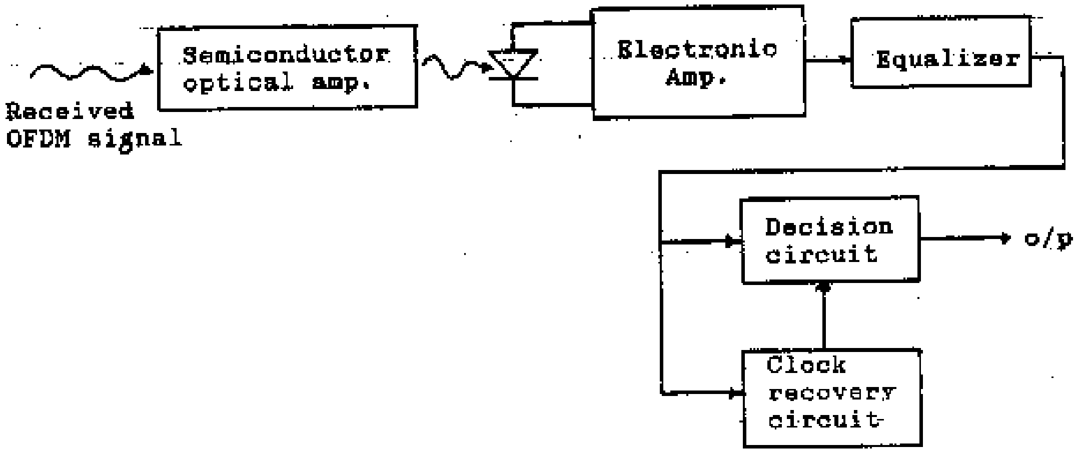


Fig. 5 A simplified block diagram of OFDM preamplified receiver.

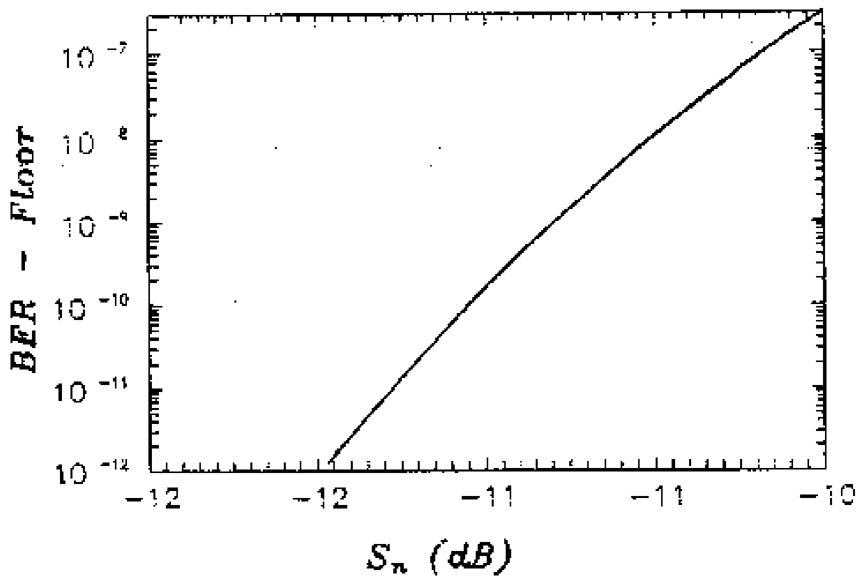


Fig. 6 Variation of BER – floor with normalized crosstalk S_n.

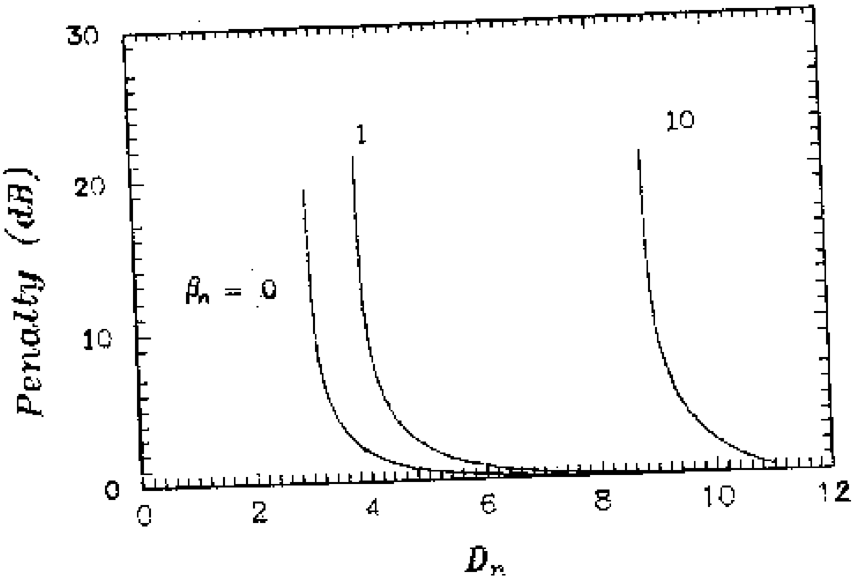


Fig.7 Crosstalk – induced penalty versus normalized channel spacing D_n for different values of β_n.

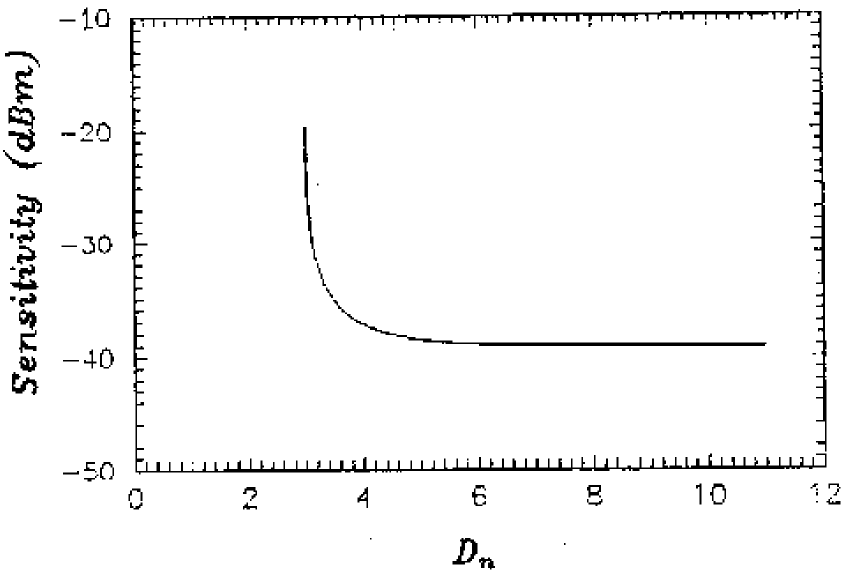


Fig. 8 Sensitivity of 10 Gbit/s – OFDM receiver against normalized channel spacing D_n.