Interaction of Semiconductor Laser Chirp with Fiber Dispersion: Impact on WDM Directly Modulated System Performance

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Abstract—In this paper, we have analyzed the interaction of semiconductor laser chirp with the fiber chromatic dispersion characteristics in order to study the impact on a Wavelength Division Multiplexing (WDM) directly modulated system performance. Also, we have demonstrated that the system transmission performance depends, strongly, on the Directly Modulated Laser (DML) output power and its adiabatic and transient chirp parameters. We have calculated by simulation, that the effect of DMLs chirp can be compensated by a negative dispersion fiber in a specific range of the DML output power. In addition, a pulse broadened by the positive dispersion fiber can be equalized using self-phase-modulation (SPM) in the optical fiber. The majority of metro and access networks are made up of conventional single-mode fibers (SMF) which are positive dispersion fibers. We have demonstrated that the optimum compensation is always feasible for such fibers by changing the optical output power in the DML laser. Furthermore, simulations suggest that this technique is able to enhance the performance of directly modulated wavelength division multiplexed systems if the power of each channel is chosen correctly.

Keywords- ***directly modulated laser; adiabatic and transient chirp; linewidth enhancement factor; adiabatic coefficient; fiber chromatic dispersion.***

I. INTRODUCTION

Direct modulation laser schemes have been used during last few years because of their intrinsic simplicity and cost-effectiveness, especially when applied to metro and access networks. However, frequency chirp characteristics of directly modulated lasers (DMLs) limit significantly the maximum achievable transmission distance over standard single-mode fibers (SMF).

A number of different approaches have been studied to improve transmission performance using DMLs, including cutting down the chirp externally using a narrow band-pass filter and the deployment of a negative dispersion fiber. With respect to this last approach, others authors have proposed their use (i.e., MetroCor™ fiber) in order to take advantage of the positive transient chirp of DMLs to increase transmission distances, [1-4]. However, typical metro and access networks installations use conventional single-mode fibers (SMF) and because of the cost and difficulty (or lack of feasibility) in changing embedded fiber links, a method that enhances system performance requiring only the modification of one or both endpoints of a link is a critical requirement.

In this work, we have demonstrated that the transmission performance depends strongly on DML output power and on its adiabatic and transient chirp. We also demonstrated that systems using SMF fibers can achieve a good performance if the DML output power is properly chosen. We have found a mathematical expression that make an estimation for a power value to fix the laser power output for each channel in WDM systems.

Section II is dealing with a short theoretical background to understand the impact of the chirp, adiabatic and transient, in DML lasers; Section III points out the system of reference characteristics (16 channel WDM) for the simulations and the different cases considered and finally in Section IV comparisons after simulations of different cases in a 32 channel WDM system are commented.

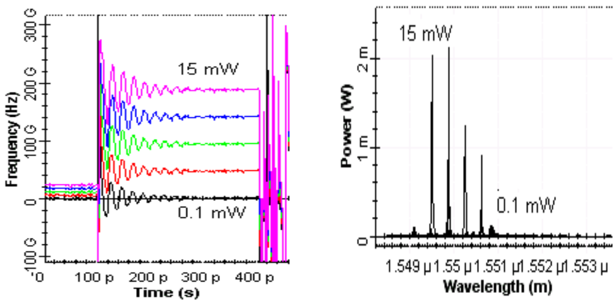
II. THEORETICAL BACKGROUND

A Distributed Feed-Back (DFB) laser which oscillates in a single longitudinal mode, under CW (Continuous Wave) operation, may experience dynamic line broadening when the injection current is directly modulated. This line broadening is a frequency chirp associated with modulation-induced changes in the carried density [5-6]. The frequency variation, $\Delta\nu$, of a DFB-DML is related to the laser output optical power, *P(t)*, through the expression, [7]:

$$\Delta\nu(t) = \frac{\alpha}{4\pi}\left\{\frac{d}{dt}\left[\ln(P(t)\right] + kP(t)\right\} \qquad (1)$$

where α is the linewidth enhancement factor [8] and *k* is the adiabatic chirp coefficient. The first term of (1), related to transient chirp, causes variations in the pulse width, while the second term (adiabatic chirp) produces a timing shift between "1" and "0" levels, depending on the output power.

The frequency chirp, due to the adiabatic chirp and shown in Figure 1 (a), implies a shift in the wavelength emission, as it shown in Figure 1 (b). The optical frequency shift from the actual laser output frequency is the principal cause of system performance variations.



(a) (b)

Figure 1. (a) Chirp and (b) Spectrum of the signal at the output DML for a power range 0.1-15 mW.

The α-parameter affects the laser bandwidth, so that large α-parameters cause increased laser spectral width. Figure 2 shows the output spectrum laser for α-parameters 1 and 10. A higher spectral width for α = 10 case is obtained.

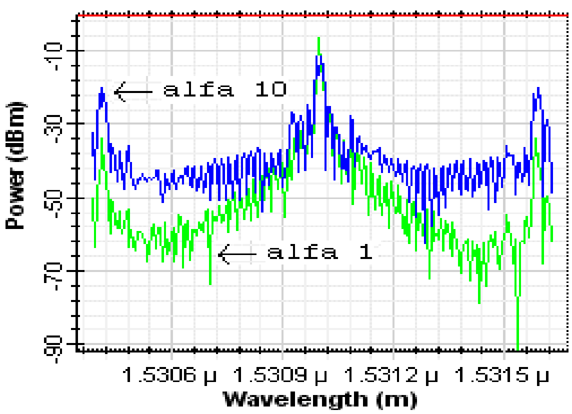


Figure 2. Output laser spectra for α = 1 and α =10.

This spectral bandwidth causes a pulse time broadening, T_1, when it goes through the fiber [9], which expression after a length z of fiber is:

$$b_f(z) = \frac{T_1}{T_0} = \left[\sqrt{\left(1 - \frac{\alpha\beta_2 z}{T_0^2}\right)^2 + \left(\frac{\beta_2\ z}{T_0^2}\right)^2} \right] \quad (2)$$

where β_2 is the group velocity dispersion parameter (GVD) and T_0 is related with the FWHM (*full width at half-maximum*) as $T_{FWHM}=2(\ln 2)^{1/2}T_0 \approx 1.665\ T_0$.

In Fig. 3, the pulse broadening parameter variation is shown. The initial pulse width chosen is $T_0 = 30$ ps (T_{FWHM} = 50 ps), for 3 different values of the α-parameter: 0, 2 and 4. In all cases there is a minimum broadening of the pulse obtaining, for this case, the best behaviour of the system.

The *adiabatic coefficient*, κ, depends on the laser structure, being the figure that takes into account the output power and the generated chirp, (1). The relationship to the photon energy, $h\nu$, optical frequency, υ, and laser quantum efficiency, η_0, confinement factor, Γ, cavity volume, V_0 and gain compression factor, ε, is in agreement with the expression:

$$\kappa = \frac{2\Gamma}{\eta_0 h \nu V_a}\varepsilon \quad (3)$$

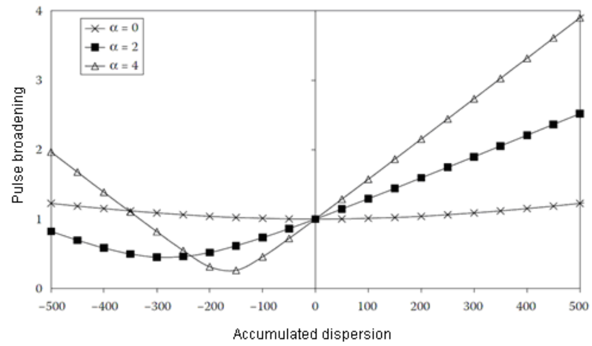


Figure 3. Pulse broadening parameter for transient chirp , at λ = 1550 nm, as a function of the accumulated dispersion, D.L

In Fig. 4 the optical spectrum for three lasers, with the same output power and different κ coefficient is shown. The wavelength of emission is 1551 nm. As bigger is the κ coefficient, wider is the spectrum and lower is the output power.

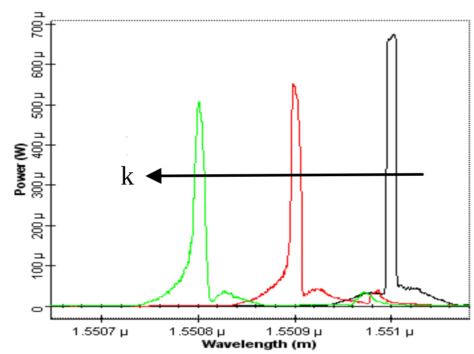
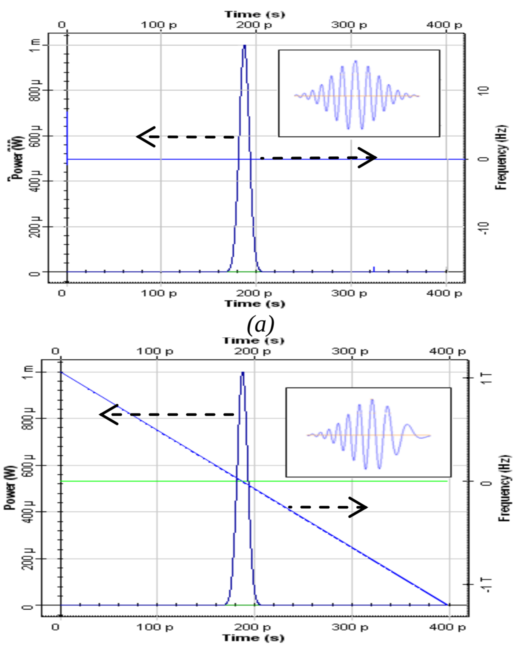


Figure 4. Laser spectrum shifting due to an adiabatic chirp with different values of κ

Laser chirping can lead to a significant dispersion effects for intensity-modulated pulses when the laser emission wavelength is displaced from the zero-dispersion wavelength of the fiber. In Fig. 5, the pulse chirp is plotted together with the pulse intensity. Whereas the input pulse is chirpless, the instantaneous frequency of the output pulse decreases from the leading to the trailing edge of the pulse. The reason for this is the Group Velocity Dispersion (GVD). In case of anomalous GVD, the higher frequency ("blue-shifted") components of the pulse travel faster than the lower frequency (or "red-shifted") ones, [10].

The effect of GVD on the pulse propagation depends, mainly, on whether or not the pulse is chirped, the laser injection pulse shape, [11-12], and also on the fiber SPM (Self Phase Modulation). With the correct relation between the initial chirp and the GVD parameters, the pulse broadening (which occurs in the absence of any initial chirp) will be preceded by a narrowing stage (pulse compression). On the other hand, the SPM alone leads to a pulse chirping, with the sign of the SPM-induced chirp, being opposite to that induced by anomalous GVD. This means that in the presence of SPM, the GVD induced pulse-broadening will be reduced (in the case of anomalous), while extra broadening occurs in the case of normal GVD.



(a)

(b)

Figure 5. (a) Output pulse shape and chirp for free chirp Gaussian pulse (b) Output pulse shape and chirp after a fiber length

III. SYSTEM OF REFERENCE

We have to point out that the transmission performance of waveforms produced by directly modulated lasers, in fibers with different signs of dispersion, depends strongly on the characteristics of the laser frequency chirp.

TABLE I. VALUES AND RANGES OF DML PARAMETERS

Parameter	**DML-T**	**DML-A**
Alpha coefficient, α	5.6	2.2
Adiabatic chirp, κ $(W.s)^{-1}$	$1.5{\cdot}10^{12}$	$28.7{\cdot}10^{12}$
Output Power range	0.1 - 15 mW	
Extinction Ratio	9 dB	
RIN (Relative Intensity Noise)	- 130 dB/ Hz	

For this reason, to study the WDM system performance, a simple arrangement is proposed. It is made up of two kinds of DFB-DMLs lasers presenting extreme behaviors: DML-A is strongly Adiabatic chirp dominated and DML-T is strongly Transient chirp dominated. The parameter values for the two simulated DMLs are shown in Table I.

We have used two kinds of optical fibers; the already laid and widely deployed single-mode ITU-T G.652 fiber (SMF) and ITUT-T G.655 fiber Recommendations with a negative dispersion sign around C band, *Non-Zero Negative Dispersion Shifted Fiber* (NZ-NDSF) (see Fig. 6).

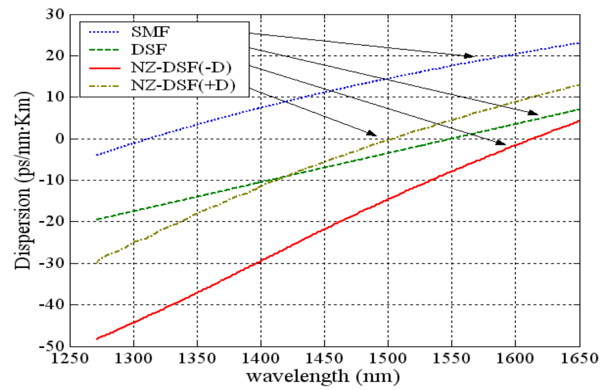


Figure 6. Dispersion Coefficient for different optical fibers

In a computer simulations, four different systems (*Cases A, B, C and D*) have been analyzed based on the optical system of Fig. 7. Table II summarize the different *Cases*.

TABLE II. ANALYZED CASES

Case	**DML**	**Fiber**
A	DML-A	SMF
B	DML-A	NZ-NDSF
C	DML-T	SMF
D	DML-T	NZ-NDSF

In this work, we are mainly interested in comparing the system performance based on the type of fiber and DML used; for this reason, the rest of link components have been modeled by considering ideal behavior. After 100 km of fiber transmission, channels are demultiplexed and detected using a typical *pin* photodiode. The system quality and its performance, in terms of *Q*-factor, is analyzed for each transmitted channel.

The *Q* factor is the signal-to-noise ratio at the decision point, in voltage or current units, and it is typically expressed by, [13]:

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0} \qquad (4)$$

where μ_i and σ_i are average values and variances of the "1" and "0" values for each pattern. $Q \approx 7.03$ corresponds to a *BER* of 10^{-12}.

Fig. 8 shows the *Q*-factor dependence on the power of the channel for the wavelength channel centered at 1551 nm.

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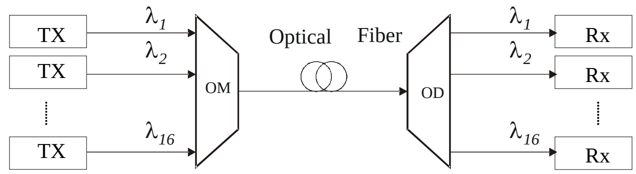
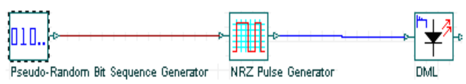
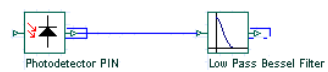
Independently of the *Case* and wavelength channels, the *Q*-factor always presents a maximum value for a specific DML output power. This behavior demonstrates the existence of an *optimum channel power* to be considered during the system design. As can be seen from Figure 8, this behavior is the same for all analyzed *Cases* but it is a result of different phenomena. For *Cases* which use adiabatic chirp dominated DML-A lasers (*A* y *B*), the Q_{max} value is reached at 0.3-0.46 mW, independently of the fiber type. In this case, the result of the interaction of the dispersion with the specific chirp characteristics produces a high intensity spike, at the front of the pulses for transmission along a fiber with positive dispersion (SMF) and, at the end for negative dispersion (NZ-NDSF) fibers. The absolute value of the dispersion (and not its sign) will play a major role in the transmission performance.



a) 16-channel WDM system



b)Tx



c) Rx

Figure 7. a) Schematic part of the complete arrangement set up; b) transmission side and c) reception side

Then, the performance corresponding to transmission along a SMF fiber will be worse than that corresponding to transmission through a NZ-NDSF fiber because of the larger absolute value of the dispersion. For small powers, the *Q*-factor increases with the power channel, $P_{ch.}$ because a large amount of power reaches the detector. For higher P_{ch} the optical pulse deformation arising from chirp induced by the DML becomes too large and causes an error in pulse reconstruction [14].

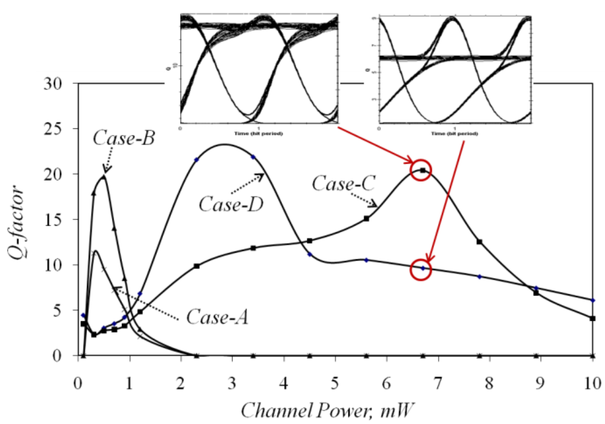


Figure 8. *Q*-factor dependence on channel power for λ = 1551 nm.

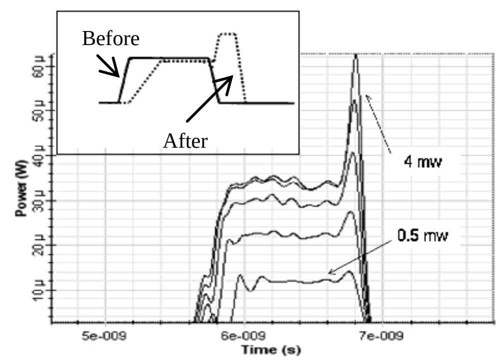


Figure 9. Shapes of optical pulses for different DML-A output powers, after transmission through a negative dispersion fiber.

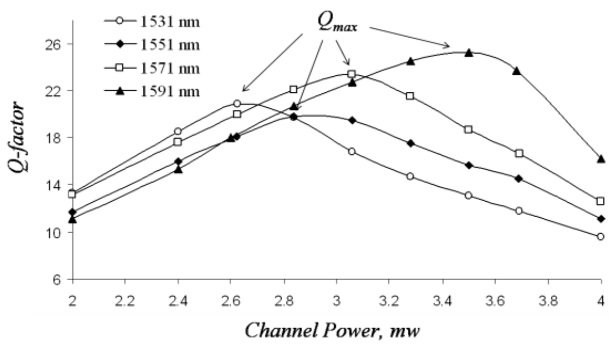
Fig. 9 represents the power waveforms for five different optical output powers (from 0.5 to 4 mW) after transmission through a NZ-NDSF fiber. As can be seen, the increment of P_{ch} will result in a higher intensity spike at the trailing edge of the pulse. As a consequence the eye pattern after transmission will be severely closed. In *Cases* which use transient chirp dominated DML-T lasers, the Q_{max} value occurs for an output power of ~ 6.7 mW for *Case-C*, or the Q_{max} is around 2.3-3.4 mW in *Case-D*.

In DML-T, the wavelength shift by laser transient chirp is a blue shift during the pulse rise time and a red shift during the pulse fall time; exactly the opposite effects takes place with SPM (Self-phase-modulation). Therefore, the optical pulse chirped by direct modulation is compressed in fibers with negative dispersion, while that chirped by SPM is compressed in fibers with positive dispersion (SMF).

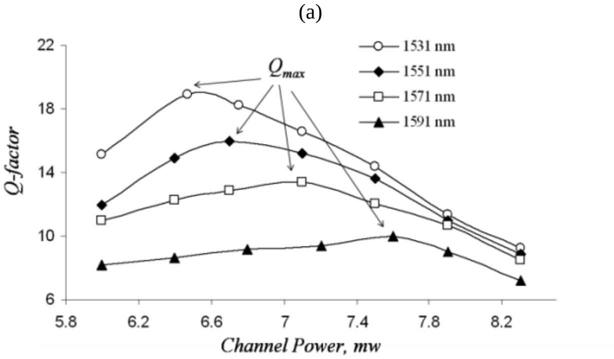
Therefore, we can conclude that systems using an SMF fiber can have a similar or better performance to those systems that use an NZ-NDSF fiber if the DML is transient chirp dominated and its output power is properly chosen.

IV. 32-CHANNEL WDM SYSTEM

In order to analyze the influence of the number of channels on the relation between P_{ch} and Q_{max} in a WDM system, simulations with a number of channels from 1 to 32 have been carried out, using the same schematic arrangement set up shown in Fig. 7. The channel wavelengths are between 1531 and 1591 nm. Some channels were located at compatibles frequencies with CWDM ITU-T grid in order to, in the future, extend this work to whole useful fiber optic spectral range (1271-1611 nm). For every case, the *Q*-factor shows a maximum value for a given optical output power.



(a)



(b)

Figure 10. *Q*-factor versus channel power for channels centered at 1531, 1551, 1571 and 1591 nm, respectively, for a 32-Channel WDM system using (a) DML-T/SMF and (b) DML-T/NZ-NDSF.

As an example, if a 32-Channel WDM system is designed using DML-T and SMF with channel powers equal to the optimum $P_{ch.}$ all 32 channels will have a *Q* higher than 8, corresponding to a BER lower than 10^{-15}. In the contrary, if a system design with equal channel power is used some of channels (higher dispersive channels) will fail after propagation along a SMF fiber.

Fig. 10 shows the *Q*-factor versus channel power for channels centered at 1531, 1551, 1571 and 1591 nm, respectively, for a 32-Channel WDM system using (a) DML-T/SMF (*Case-C*) and (b) DML-T/NZ-NDSF (*Case-D*). In both cases, each channel presents a different optimum P_{ch}. Then, by the $P_{ch.}$ control of each channel it is possible to reach the Q_{max} and an enhancement of the WDM system performance can be achieved. This optimum P_{ch} is the conclusion of the following considerations: for low power levels, below the optimum power, the *Q-factor* increases with P_{ch} because a larger amount of power reaches the detector and the performance enhancement will be dependent upon the level power, so that the greater the power in the receiver, higher system performance is obtained; while, for P_{ch} higher than optimum power, the chirp increases with level power and it causes greater frequency shift and linewidth broadening which results in an error in pulse reconstruction.

Optimum P_{ch} depends on fiber optic dispersive characteristics as well as on link length. The optimum channel powers (P_{ch} to reach Q_{max}) are plotted as a function of dispersion in Fig. 11 (open circles in the case of transmission through positive dispersion fiber and solid circles for negative dispersion fiber).

In Figure 11, the results for a channel centered at 1551 nm as well as a potential CWDM channel centered at 1391 nm, after transmission over 100 km of SMF and NZ-NDSF fibers, are shown. Attenuation dependence with wavelength was taken into account in the calculation of optimum P_{ch} and, in all cases, a $Q_{max} > 7$ (BER < 10^{-12}) was obtained.

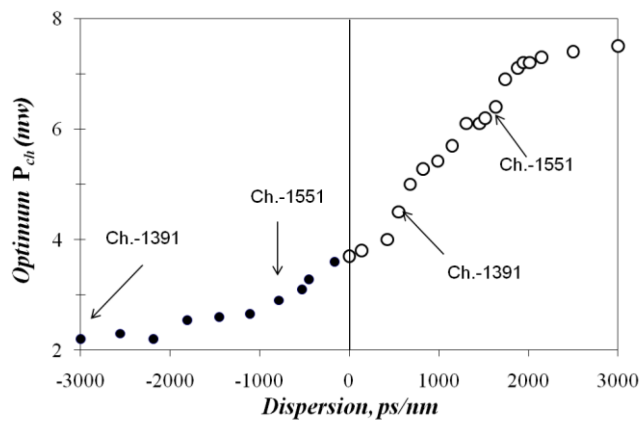


Figure 11. Comparison of Optimum Channel Power versus accumulated dispersion for a positive dispersion fiber (open circles) and negative dispersion fiber (solid circles)

A mathematical expression that fits this curve would be very useful, since it would make an estimation of the power value to fix the laser output for each channel. For this reason, using the Matlab simulation tool, this function has been estimated from a polynomial expression of degree 4 (Fig. 12):

$$f(x) = ax^4 + bx^3 + cx^2 + dx + e \quad (5)$$

a = -3.482 $\cdot 10^{-14}$; b = -6.588$\cdot 10^{-11}$; c = 4.202$\cdot$10-^{07};
d = 0.001435; e = 3.673

where x is the dispersion accumulated across the link.

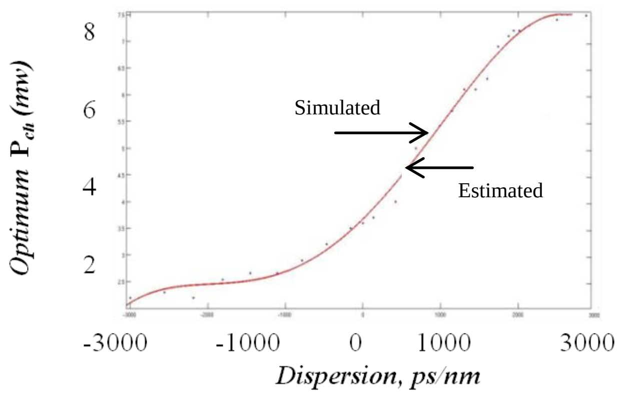


Figure 12. Estimated curve for optimum channel power

V. CONCLUSIONS

The performance of fibers relative to positive or negative dispersion characteristics is discussed for the case of directly modulated lasers. The effects of chirp and fiber nonlinearity in a directly modulated 2.5-Gb/s transmission system have been investigated by simulation. We can conclude that systems using SMF fiber can have a similar or better performance to those systems that use NZ-NDSF fiber if the DML is transient chirp dominated and its output power is properly chosen. From Fig. 8 we can conclude that DMLs transient dominated chirp are better controlled to compensate dispersion in both SMF and NZ-NDSF fibers.

Since the magnitude of chirp can be changed by controlling the optical power, the balance between SPM, chromatic dispersion and laser transient chirp can be controlled. Therefore, an optimum compensation condition can be achieved by controlling the optical DML output power. To analyze the effectiveness of this technique for WDM systems, simulations varying the number of channels from 1 to 32 have been carried out and checking. In every case, *Q*-factor shows a maximum value depending on the optical power of each channel and accumulated dispersion. This maximum value decreases depending on the number of channels used. Also, we have shown that the control of the channel power could improve the performance of each channel as well as the whole WDM system.

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