Dispersion Compensation in Metropolitan Networks Using Chirped Light Sources

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Abstract Fiber dispersion is compensated in Metroplitan networks using chirped light sources. Both electroabsorption and directly modulated lasers are considered. Eye-closure penalty of the proposed system is calculated showing a negative penalty over different distances in a wide range of the affecting parameters which include linewidth enhancement factor, adiabatic chirp coefficient, the system average power and bit rate.

Keywords: fiber dispersion, chirped light source, electroabsorption modulators, directly modulated laser, dispersion compensation, eye-closure penalty, linewidth enhancement factor, adiabatic chirp coefficient.

1. Introduction

In metro area networks, the dispersion-induced waveform distortion is the major impairment that the designer of the system has to consider. Depending on the choice of the optical transmitter, and consequently its frequency-chirp characteristics, the dispersion-induced waveform distortion can be deleterious for the signal transmission, even at very short distances. Dispersion compensation is used in point to point long-haul systems to reduce dispersion-induced penalties. However, in optical networks the placement of the dispersion compensating modules (DCM) becomes an issue because (a) different optical channels in a fiber originate from different nodes, and hence, see different amounts of accumulated dispersion, (b) the loss added by the dispersion compensating modules increases the effective noise figure of the system and limits the size of the network in noise-limited systems, and (c) dispersion compensation adds a cost. Therefore, an optical fiber with a dispersion-optimized design for Metropolitan area applications that will eliminate the need for dispersion compensation should ease the engineering of the network [1].

The interaction of a positive chirp with the positive dispersion of conventional standard single-mode fibers (SMF), like Corning SMF-28 fiber or any other fiber with similar dispersion characteristics, deteriorates the optical signal and limits the maximum achievable transmission distance [2-4]. Recently, a nonzero dispersion-shifted fiber with a negative dispersion (e.g., Corning MetroCor fiber) was introduced to take advantage of the positive chirp characteristics of low-cost transmitters that are likely to be used in metro area networks [1]. This dispersion-optimized optical fiber can eliminate the need for DCMs. This is because the dispersion is equivalently compensated through the interaction of the positively chirped source with the negative dispersion fiber (NDF).

The choice of the optical transmitter and its associated characteristics will determine the maximum distance that the signal can be transmitted. Recently, cost-effective directly modulated lasers (DMLs) have attracted much attention for a 2.5 Gbps operation for applications in networks and Metropolitan-area systems [4]. They present the advantages of small-size, low-cost, low driving voltage, and high available output power. However, their major drawback is that their chirp characteristics can significantly limit the maximum achievable transmission distance over conventional single-mode fibers [4]. NDFs can be used to take advantage of the positive chirp characteristics of DMLs to enhance the transmission distances [2]. Electroabsorption modulator integrated distributed feedback lasers (EAM-DFBs) have also attracted much attention as cost-effective transmitters for 10 Gbps applications [2] and [4].

The following investigation provides a simple phenomenological model of electroabsorption modulators, taking in account the dependence of the chirp on the applied bias voltage presented in Sec.2. This is followed by the model of DMLs that considers both adiabatic and transient chirp components in Sec.3 that also includes the eye closure penalty as a function of the linewidth enhancement factor, α. Finally, Sec.4 illustrates the simulation results obtained when varying the different affecting parameters. Section 5 summarizes the main results of this work.

2. Modeling of Electroabsorption Modulated Lasers

Generally, the performance of transmission systems which use EAMs and nondispersion shifted optical fibers is a strong function of the modulator chirp, optical extinction ratio and average transmitted optical power. The chirp and extinction ratio characteristics depend on the change in the relative refractive index of the absorption layer in the p-i-n waveguide with the applied voltage. The dependence of the real and imaginary components of the refractive index on the applied voltage is often quantified by the α-parameter and absorption, both of which are readily measurable quantities. To accurately assess the transmission system performance, a particular attention must be given to the modulator chirp and optical extinction ratio due to the rather subtle effect that they have on the bit error ratio [5].

Under small signal conditions, the value of the α-parameter, α_m, is often assumed to have a constant value. This leads to the result that the electric field of the modulator output signal is given by [5]:

$$E(V) = I(V)^{(1+j\alpha_m)/2}, \tag{1}$$

where I(V) is the voltage-dependent intensity of the signal, given by:

$$I(V) = \exp(-\gamma(V)L'), \tag{2}$$

and

$$\alpha_m = \frac{2d\Phi(V)}{d(\ln(I(V))}. \tag{3}$$

$\gamma(V)$ is the power attenuation constant, L' is the product of the modulator length and the waveguide confinement factor, and $\phi(V)$ is the phase of the optical signal. An equivalent form of α_m for an EAM is [5]:

$$\alpha_m = \frac{dn'(V)}{dn''(V)}, \tag{4}$$

where dn and dn'' are the changes in the real and imaginary parts of the refractive index of the absorption layer due to an applied voltage.

In practice, α_m is a nonlinear function of the bias voltage applied to the modulator. In this case, the output signal from the EAM in response to an applied voltage can be determined by [5]:

$$E(V) = I(V)^{1/2}\exp\left(\frac{j}{2}\int\alpha_m(V)d\ln(I(V))\right). \tag{5}$$

While (5) is an accurate result, it is not the most convenient form for simulation purposes when empirical equations for $\alpha_m(V)$ and I(V) are obtained from a fitting to measured results. The determination of the argument of the exponential function in (5) requires function evaluation and integration. The modulator output signal given by (5) can also be written, in the convenient form $I^{(1+j\alpha)/2}$ using a voltage-dependent parameter $\alpha_r(V)$, as:

$$E(V) = I(V)^{(1+j\alpha_r(V))/2}. \tag{6}$$

A comparison of the phase terms in (5) and (6) yields:

$$\alpha_r(V) = \frac{1}{\gamma(V)}\int\alpha_m(V)d\gamma(V). \tag{7}$$

Equation (7) indicates how the attenuation constant γ(V) and $\alpha_m(V)$ jointly combine to determine $\alpha_r(V)$. Using (6), with $\alpha_r(V)$ determined from measurements of $\alpha_m(V)$ and I(V), the evaluation of the argument of the exponentiation only requires a function evaluation. This is beneficial when extensive simulations are performed which involve changes to the applied voltage [5].

The dependence of the measured absorption I(V) and the α-parameter $\alpha_m(V)$ on the applied voltage is illustrated in Fig. 1 for a multiquantum-well electroabsorption modulator (MQW EAM) integrated with DFB laser.

It is clear, from Fig.1, that the α-parameter is tunable and thus the chirp is tunable. This means that the sign of the chirp parameter, α, could be set opposite to the sign of the dispersion parameter, D. For example, when using an NDF, the reverse bias voltage of the EA-DFB modulator should be adjusted so that the α-parameter is positive in order to compensate the dispersion in the fiber, and vice versa.

3. Modeling of Directly Modulated Lasers

The transmission performance of waveforms produced by directly modulated lasers over fibers with different signs of dispersion and also different absolute dispersion values strongly depends on the characteristics of the laser frequency chirp. Commercially available directly modulated DFB semiconductor lasers exhibit significant variations in their instantaneous power and frequency waveforms between different manufacturers or between different samples of the same manufacturer. A classification of the laser behavior based solely on their transient and adiabatic chirp is proposed in [6].

The instantaneous angular frequency deviation of a directly modulated DFB laser is approximately related to its output optical power P(t) through [7]:

$$\Phi(t) = \frac{\alpha}{2}\left[\frac{1}{P(t)}\frac{dP(t)}{dt} + \kappa P(t)\right], \qquad (8)$$

where α is the linewidth enhancement factor and κ the adiabatic chirp coefficient. In (8), the first term is called "transient" chirp, and the second term is called "adiabatic" chirp. It is assumed that the output power is sinusoidally modulated as:

$$P(t) = P_o(1 + 2m\cos\omega_m t), \qquad (9)$$

where P_o is the transmitted average power, m is the intensity modulation (IM) index, and $f_m(=\omega_m/2\pi)$ is the modulation frequency. This analog waveform can be considered as a special case of a digital waveform composed of alternating ones and zeros, with a bit rate equal to $R_b = 2f_m$ and an extinction ratio given by [7]:

$$\frac{(1+2m)}{(1-2m)}. \qquad (10)$$

It can be shown that the eye closure penalty for small IM indexes (m<<1) is to a first-order approximation equal to [7]:

$$P_{oe}^{CO} = \left\{[\cos\Phi(\omega_m) - \alpha\sin\Phi(\omega_m)]^2 + \beta^2\sin^2\Phi(\omega_m)\right\}^{-0.5} \quad (11)$$

In (11), $\phi(\omega_m)$ is a dimensionless parameter defined as:

$$\Phi(\omega_m = \pi R_b) = \frac{\pi\lambda^2 R_b^2 DL}{4c}, \qquad (12)$$

where λ is the carrier wavelength of the transmitted optical waveform, D is the fiber dispersion parameter, L is the fiber length, and c is the velocity of light in vacuum. In (11), β is the frequency modulation index defined as:

$$\beta = \frac{\kappa\alpha P_o}{\omega_m}, \qquad (13)$$

where κ, the adiabatic chirp coefficient, is defined as [8]:

$$\kappa = \frac{\alpha}{4\pi}\left(\frac{2\Gamma\varepsilon\lambda}{V\eta_o hc}\right), \qquad (14)$$

with η_o is the differential quantum efficiency, Γ the confinement factor, V the volume of the active layer, ε the non linear gain compression factor and h Planck's constant.

4. Simulation Results and Discussion

The aforementioned EA-DFB model was used in simulations performed in [1]. The simulations compared the performance of 10 Gb/s signals over SMF-28 and MetroCor fibers. The sign of the chirp-parameter was set opposite to the sign of the dispersion of the fiber in each case by properly adjusting the reverse bias voltage of the electroabsorption session. The simulations covered wavelengths at the outer edges of the C- and L-bands (1530 and 1622 nm, respectively) for both fiber types. It is shown that for a channel-wavelength 1622 nm, the transmission over MetroCor fiber shows a negative penalty for distances up to 600 km, while transmission over SMF-28 fiber shows a penalty of 2 dB at a distance of 80 km [1]. Verifying the simulation results presented in for β = 0.707, we have obtained almost the same results (with a max difference = 4%) as shown in Fig.2.

The parameters affecting the eye closure penalty are varied in order to obtain the maximum distance, L_m, over which the penalty is negative and the obtained results are displayed in Fig.3 according to the following parameter values: $\alpha = 9$, $\kappa = 29E12$ Hz.W^{-1}, $D = -3$ ps.nm^{-1}.km^{-1}, $\lambda = 1622$ nm, and $P_o = 1$ mW.

The maximum parameter values represented in [1] are chosen, which lead to the maximum L_m (obtained graphically) at different bit rates as follows: L_m= 89.5 km at 40 Gbps, L_m= 358 km at 20Gbps, and L_m= 1462 km at 10Gbps. Furthermore, we studied the effect of each parameter separately. Firstly, considering the effect of P_o, one has obtained the results presented in Figs.4 and 5.

Comparing the results shown in Fig.5, it is easy to note that at P_o=10 mW, the value of L_m exceeds that at P_o=2mW by approximately 4.5% at 40Gbps. At 20 Gbps, L_m is found to be also 4.5% larger in the case of larger P_o, while at 10 Gbps, it is limited to less than a 4% increase for the larger P_o.

The values used in simulation results presented in Fig.5 are similar to those presented in Fig.3, but taking α=7, and κ=8E12 Hz.W^{-1}(representing a DML that is neither strongly adiabatic nor transient chirp dominated). It is clear that increasing the average transmitted power, P_o, leads to an increase in the distance L_m over which the eye closure penalty is negative.

Secondly, considering the effect of α is presented in Figs.6 and 7 at R_b= 40 Gbps, where L_m is found increasing with α.

The effect of κ is illustrated in Fig.8, showing minimum (negative) penalties around 50 km. When the effects of α, and κ are combined, one gets a more significant change in L_m as shown in Fig.9. It is clear that L_m increases by 50% more than when considering the separate effect of each parameter. It must be mentioned that the effect of optimizing D and α does not appear if κ exceeds a certain value (typically 1.5E13). This value of κ was achieved when considering the parameter values affecting κ presented in [9]. The value of κ is also influenced by the quantum efficiency,η, as shown in Fig. 10.

Finally, the relationship between the penalty and the wavelength at different bit rates is studied and results are displayed in Figs. 11 and 12. One can notice that the penalty is equal to zero near 1650 nm; this is because the value of D is equal to zero at 1650 nm for MetroCor fiber. The case of 40 Gbps is also considered resulting in a negative penalty at distances less than 25 km.

It must be noted that the eye closure penalty arising from only dispersion was calculated without taking the receiver structure into account, which would affect the BER.

5. Conclusion

The chirp induced optical sources can be useful in dispersion compensation when a dispersion-optimized fiber is used depending on the transmitter chirp characteristics. This compensation can be obtained either by varying the chirp parameter of the source (in case of using EA-DFBs) with a standard single-mode fiber or using an NDF a positively chirped source. To obtain the maximum distance, L_m, over which the penalty is negative, the affecting parameters are varied, including α, κ, P_o, λ and R_b. Keeping P_o constant, this distance is found exceeding 94, 376, and 1520 km at 40, 20, and 10 Gbps respectively. Both α and κ showed, separately, a limited effect on L_m, but when combined, one can obtain more than 50% increase in L_m. In the wavelength band 1450-1640 nm, a negative penalty is obtained at distances up to 150 km at 10 Gbps and 75 km at 20 Gbps. The wavelength band is stopped at1640 nm at which the dispersion of the MetroCor NDF reaches zero.

6. References

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7. Appendix

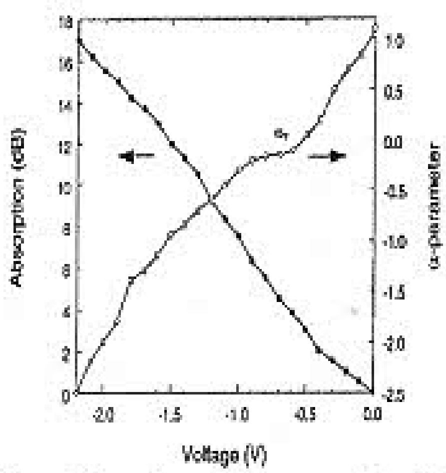

Figure 1: Dependence of the measured absorption and α-parameter α_m on the applied voltage for an MQW-EAM integrated with a DFB laser reported in [5].

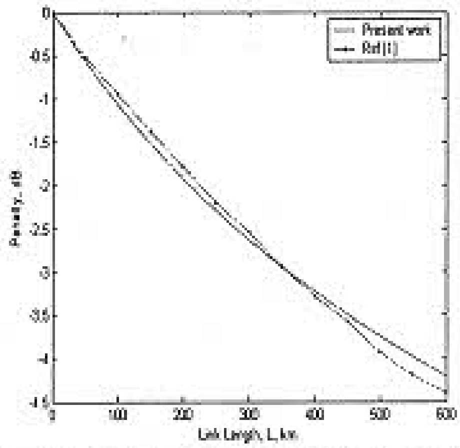

Figure 2: Eye closure penalty versus fiber length at 2Gbps.

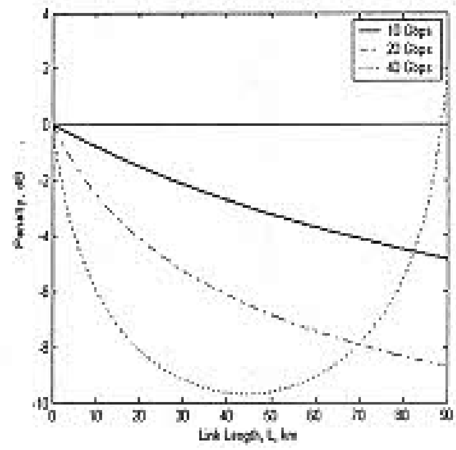

Figure 3: Eye closure penalty versus fiber length for different bit rate systems.

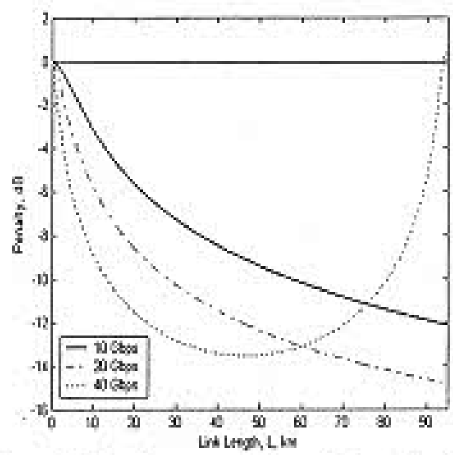

Figure 4: Eye closure penalty at P_o = 10 mW at different bit rate systems.

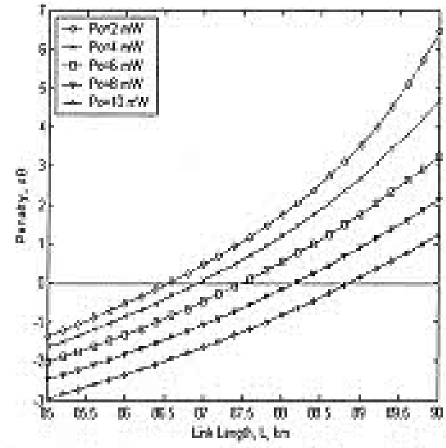

Figure 5: Eye closure penalty at 40Gbps: effect of the average transmitted power, P_o.

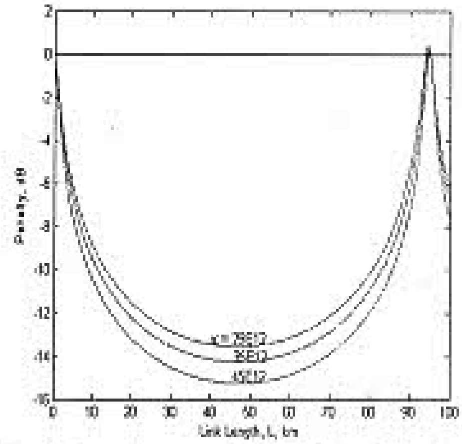

Figure8: Eye closure penalty at 40Gbps: effect of the adiabatic chirp coefficient, κ.

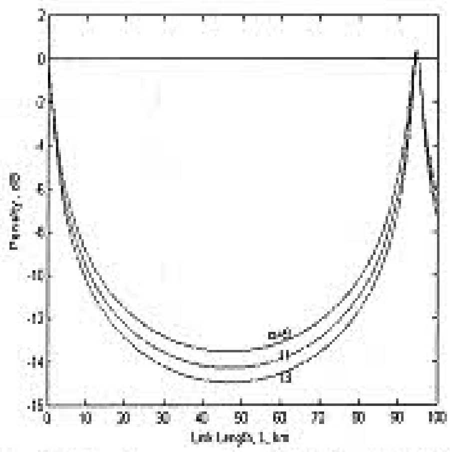

Figure 6: Eye closure penalty at 40Gbps: effect of the linewidth enhancement factor, α.

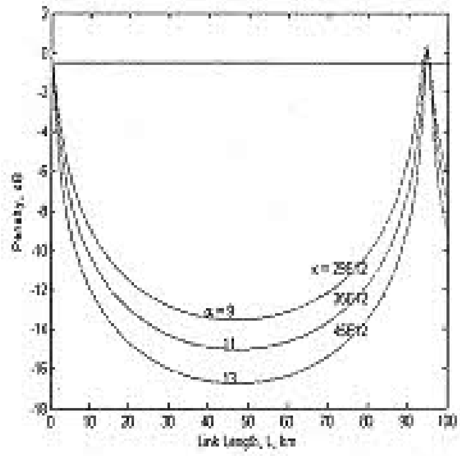

Figure 9: Eye closure penalty at 40Gbps: effect of combined α and κ.

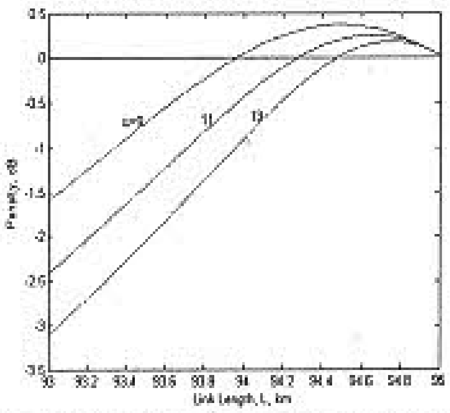

Figure 7: Dependence of the distance over which the penalty is negative, L_n, on the linewidth enhancement factor, α.

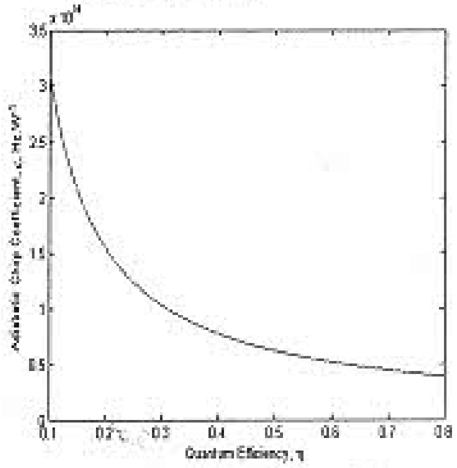

Figure 10: The effect of the quantum efficiency, η on the adiabatic chirp coefficient, κ.

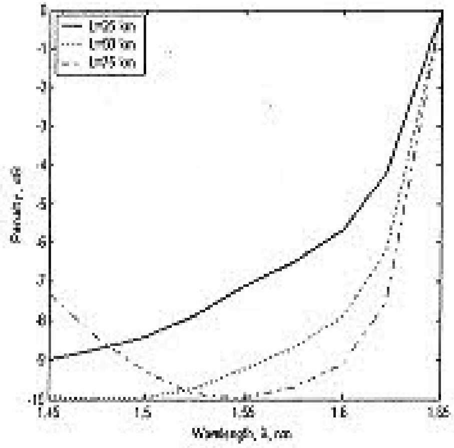

Figure 11: Eye closure penalty versus wavelength, λ, at different fiber lengths at 20 Gbps.

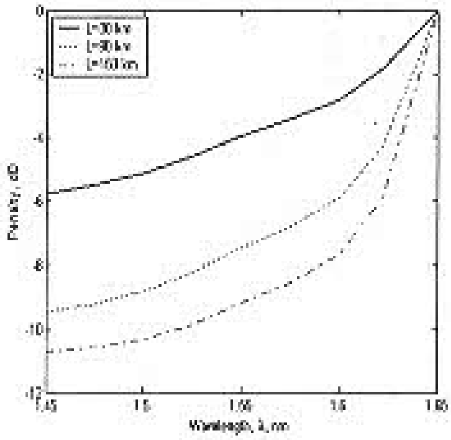

Figure 12: Eye closure penalty versus wavelength, λ, at different fiber lengths at 10 Gbps.