THE ANALYSIS OF AN OPTICAL FIBRE COMMUNICATION SYSTEM USING LASER RATE EQUATIONS

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ABSTRACT

Fibre dispersion has been the main limitation to high-speed data transmissions employing optical fibres. Various techniques and methods for combating this limitation have therefore been proposed. Such techniques include electrical and optical dispersion compensation, optical and electrical pulse shaping, and modifications of the fibre dispersion profiles. Some of these techniques and methods have resulted into very effective but expensive systems, and it has been difficult to adopt them. Others have resulted into inexpensive systems with moderate performance, and some of these have been adopted. In the present paper, the effect of electrical pulse shaping on dispersion-induced pulse distortion is investigated by computer simulation techniques. The results show that the detrimental effects of the dispersion can be greatly reduced without incurring very high costs. Moreover, this method is applicable to systems employing standard optical fibres, the major component in the already installed systems.

INTRODUCTION

The emergence of optical fibre communication technology has opened new communication possibilities which are rapidly replacing conventional means of communication for a number of reasons. First, optical fibres have higher transmission capacity than metallic cables and are therefore better suited to the increase demand for high transmission capacity. Secondly, optical fibres provide higher security to the transmitted information in terms of eavesdropping and interference. Thirdly, optical fibre cables are smaller, lighter and more robust than metallic cables. Optical fibre technology is also advantageous to developing countries, where the installed communication infrastructure is minimal. It has therefore been argued that, such countries can leap-frog in technology by basing their current and future telecommunication installations on optical fibres (Kai-Li 1987).

In spite of the higher transmission potential promised by optical fibres, a number of factors have emerged as limitations to their maximal utilisation. These factors include the speed of the electronics, fibre attenuation, fibre dispersion and detector noise (Veith 1990). Except for fibre distortion, the effects of the other problems have been substantially reduced through applied research. Fibre dispersion distorts the optical pulses transmitted through them by causing them to broaden and break into multiple pulses (Capmany & Muriel 1991, Kundaeli 1998). In conventional systems, which constitute most of the already installed systems, transmission is carried out at 1300 nm where the optical fibres have zero dispersion. However, better transmission can be achieved at 1500 nm because then the optical fibres have minimum attenuation. Efforts have therefore been carried out to combat the dispersion at 1500 nm and take advantage of the lower attenuation by modifying the dispersion profiles of the optical fibres. Such modified fibres include dispersion flattened ones in which the fibre dispersion is more or less flat in the range 1300 - 1500 nm, and dispersion shifted ones, in which the zero dispersion window has been shifted from 1300 nm to 1500 nm (Nuyts *et al.* 1997). Other efforts have focused on the processing of the optical pulses (Koch & Alferness 1985) and the use of dispersion-insensitive solitons (Kodama & Hasegawa 1992). Such techniques (modified fibres and special optical pulses) tend to raise the costs of the optical fibres and the attendant communication systems. Moreover, such techniques are not suitable where conventional fibres have already been laid down. As a result, efforts have been carried out to find alternative solutions to the dispersion problem in conventional optical fibres and have included equalization (Iwashita & Takachio 1990) and optical phase conjugation (Gnauk *et al.* 1993).

One of the promising techniques proposed for conventional optical fibres is that of shaping the electrical pulses so that the transmitted optical pulses suffer least distortion as they propagate within the fibre. The present paper attempts to show that if indeed proper shapes are chosen for the current pulses used to modulate the laser, then the effects of dispersion can be greatly reduced. The analysis is based on computer simulation, a technique which is quite cost effective. Moreover, the rate equation model of the laser is used, because results which are obtained by using this model closely approach those of practical systems. The model is therefore used in the analysis and design of practical optical fibre communication systems (Rambech & Røyset 1990).

METHODS

System model and Analysis

The model of the communication system analyzed in the present paper is given in Fig. 1. The laser is driven by a data source which transforms the digital data into current pulses represented by $I(t)$. The laser output power is represented by $P(t)$ and its phase by $\varphi(t)$. The optical fibre has length z and is represented by its impulse response $h(t,z)$, and output power $P(t,z)$. The operation of the laser is best represented by its rate equations. This representation is necessary because the processes taking place within the laser are so inter-dependent that the output power and phase need to be described in terms of coupled non-linear differential equations. The input-output relationships of the laser are then specified by the (rate) equations (Cartledge & Burley 1989).

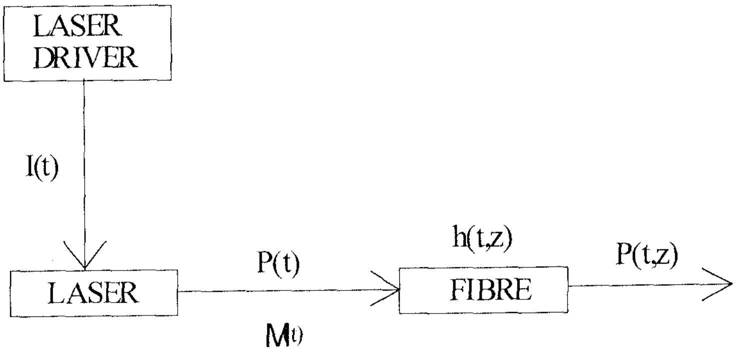

Fig. 1: Model of the analyzed optical fibre communication system

$$\frac{dS}{dt} = \Gamma G(N - N_0)S - \frac{S}{\tau_p} + \frac{\beta \Gamma N}{\tau_n}$$

$$\frac{dN}{dt} = \frac{I(t)}{qV_a} - G(N - N_0)S - \frac{N}{\tau_n}$$

$$\frac{d\phi(t)}{dt} = \frac{1}{2}\alpha\left[\Gamma v_g a_0 (N - N_0) - \frac{1}{\tau_p}\right] \tag{1}$$

where

$$G = \frac{v_g a_0}{1 + \varepsilon S} = \frac{g_0}{1 + \varepsilon S} \tag{2}$$

S = photon density in the active layer, N = electron density in the active layer, $\varphi(t)$ = phase of the optical signal, I = modulating current into the laser, ^{1} = mode confinement factor, v_g = group velocity, a_0 = active layer gain coefficient,

$g_0 = v_g a_0$ = active layer gain, ε = gain compression factor, τ_p = photon lifetime, β = mode spontaneous gain, τ_n = electron life time, α = linewidth enhancement factor, V_a = volume of the active layer region, η_0 = total differential quantum efficiency, and N_0 = carrier density at transparency.

Using this representation, the instantaneous power and phase can be obtained by integrating the rate equations (Cartledge & Burley 1989).

In this analysis, we seek to represent the rate equations in terms of the power at the output of the laser. We therefore represent the instantaneous power and chirp at the output of the laser by

$$P(t) = \frac{1}{2} S(t) \frac{V_a \eta_0 h\nu}{\Gamma \tau_p}$$

$$\Delta\nu(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt} \tag{3}$$

where ν = the optical emission frequency of the laser and h = Planck's constant.

We then use $P = P(t)$ and rewrite the rate equations in the form

$$\frac{dP}{dt} = \Gamma G(N - N_0)P - \frac{P}{\tau_p} + \frac{V_a \eta_0 h\nu\beta}{2\tau_p \tau_n} N$$

$$\frac{dN}{dt} = \frac{I(t)}{qV_a} - \frac{2\Gamma\tau_p G(N - N_0)}{V_a \eta_0 h\nu} P - \frac{N}{\tau_n}$$

$$\frac{d\phi(t)}{dt} = \frac{1}{2}\alpha \left[\Gamma v_g a_0 (N - N_0) - \frac{1}{\tau_p} \right] \tag{4}$$

where in this case

$$G = \frac{g_0 V_a \eta_0 h\nu}{V_a \eta_0 h\nu + \varepsilon 2\Gamma \tau_p P} \qquad (5)$$

The modulating current signal $I(t)$ in Fig. 1 is given by

$$I(t) = I_b + \sum_{m\ -\infty}^{\infty} a_m I_m(t - mT) \qquad (6)$$

where I_b is the dc bias current, $I_m(t)$ is the basic modulating current pulse, T is the duration of a modulating current pulse and $a_m = 0$ or 1.
For the fibre, we use its conventional model in which the transfer function is given by

$$H(\omega, z) = e^{-\sigma z} e^{j\frac{\lambda_0^2 D_g \omega^2 z}{4\pi c}} \qquad (7)$$

where σ is the attenuation constant of the fibre, D_g is the group velocity dispersion parameter of the fibre, λ_0 is the central emission wavelength of the laser and c is the speed of light in free space.
We then use FFT techniques to compute the power at the output of the fibre from the Fourier transform relations

$$P(t) \Leftrightarrow P(\omega)$$

$$P(\omega, z) = P(\omega) \bullet H(\omega, z) \bullet H^*(\omega, z) \qquad (8)$$

$$P(t, z) \Leftrightarrow P(\omega, z)$$

where $P(\omega)$ is the Fourier transform of $P(t)$, $P(\omega, z)$ is the Fourier transform of $P(t,z)$, and $\Leftrightarrow$ relates a function and its Fourier transform respectively.

RESULTS AND DISCUSSION

The results from the analysis are presented in Figures 2a to 6b. In all of these results, the values of the component parameters and the modulating current are given in Tables 1 to 3.

Table 1: Parameters for the optical fibre used

Symbol	Name	Value
L	length	50 km
D_g	group velocity	20 ps^2/km.nm
σ	attenuation	0.2 dB/km

Table 2: Parameters for the laser diode

Symbol	Name	Value
Γ	mode confinement factor	0.4
v_g	group velocity	8.5E+9 cm/s
a_0	active layer gain coefficient	2.5E-16 cm^2
e	gain compression factor	2.5E-17 cm^3
t_p	photon lifetime	3 ps
β	mode spontaneous gain	3.0E-5
τ_n	electron life time	1 ns
α	linewidth enhancement factor	5
V_a	volume of active layer region	1.5E-10 cm^3
η_0	total differential quantum efficiency	0.4
N_0	carrier density at transparency	1.0E+18 cm^{-3}
λ	emission wavelength of the laser	1550 nm

Table 3: Drive current and data parameters

Symbol	**Name**	**Value**
I_b	bias current	38 mA
I_m	modulation current	28 mA
R	data transmission rate	2.4 Gbits/s
ι	pulse rise time	100 ps
B	data sequence	0 1 1 0 0 1 0 1

The laser parameters used in this report are the same as those used in the report of Cartledge & Burley (1989), and results based on laser parameters from elsewhere (Atlas *et al.* 1988, Cimini *et al.* 1990), were found to show the same pattern. From figure 2 (a-d) we see that there is an overshoot in both the laser power and chirp at the application of the current drive pulse. Also, both the laser power and the laser chirp show big excursions whenever the drive current changes rapidly. On the other hand, the fibre output power follows the laser output power quite closely. Below are presented results of only the fibre output power because the laser power and the laser chirp follow the same pattern explained above. The case in which the input current is smoothed by an RC network is indicated in figure 3 (a and b). In these results we see that the overshoots in the fibre output have been reduced. The results obtained so far resemble those obtained by Cartledge and Burley (1989) and Rambech and RØyset (1990). From figure 4 (a and b), we see that the use of trapezoidal current pulses enables one to detect the received pulses separately. However, the fibre output shows a significant overshoot, which is reduced when a pedestal is added on the leading edge of the pulses, as shown in figure 5 (a and b). Finally, as shown in figure 6 (a and b), the use of trapezoidal pulses with pedestals on both the leading and trailing edges leads to narrower pulses, whose shape is different from the shape of the original pulses, than in the case of trapezoidal pulses with pedestals on the leading edges only.

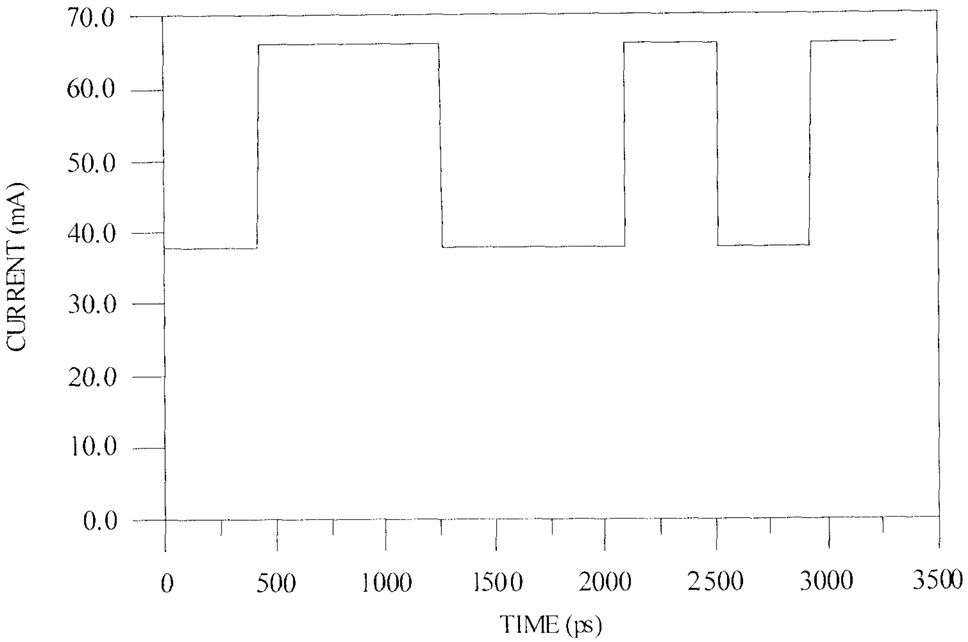

Fig. 2a: Laser drive current for bit sequence 01100101

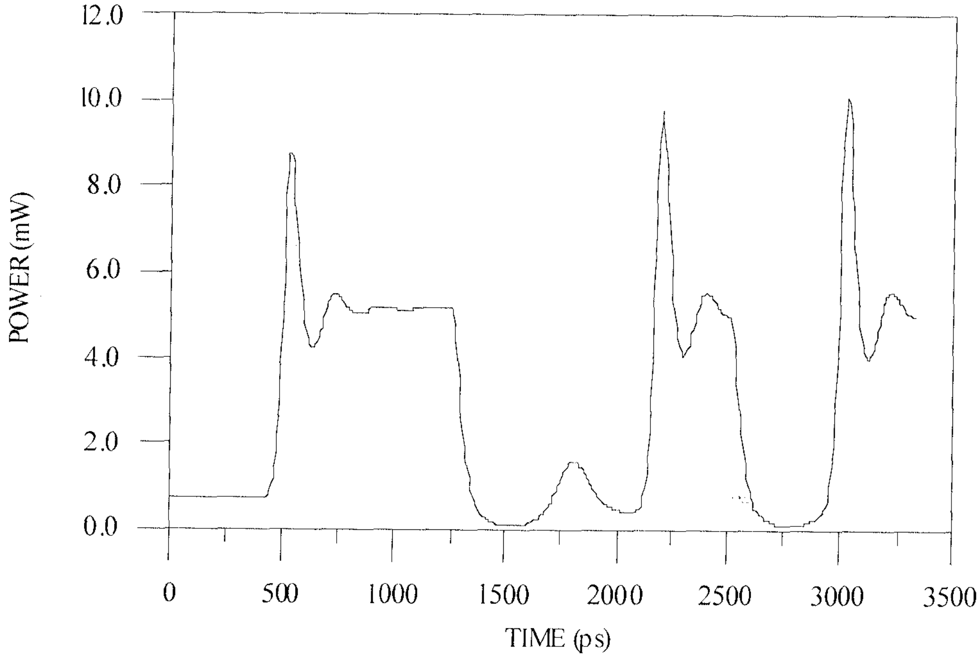

Fig. 2b: Laser output power at R = 2.4 Gbit/s

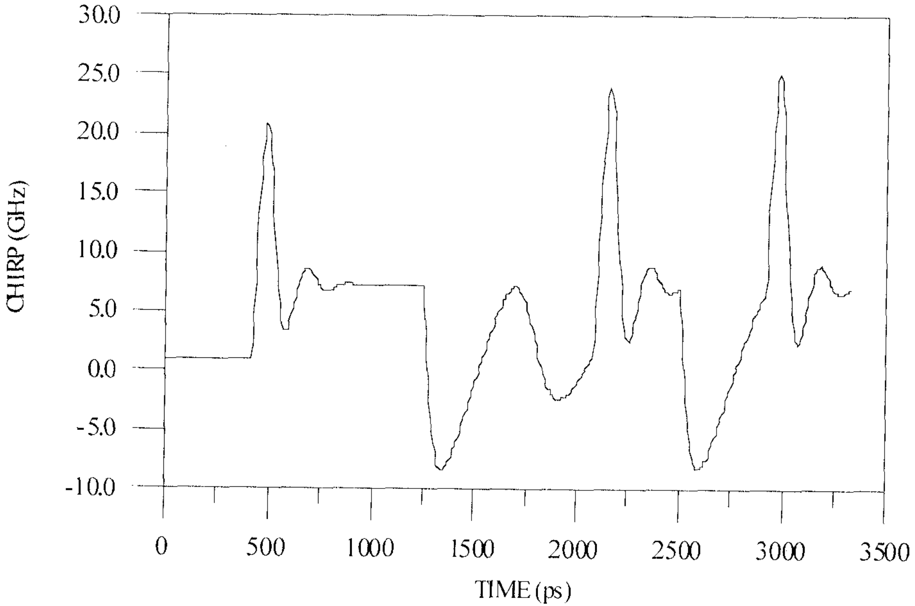

Fig. 2c: Laser output chirp at R = 2.4 Gbit/s

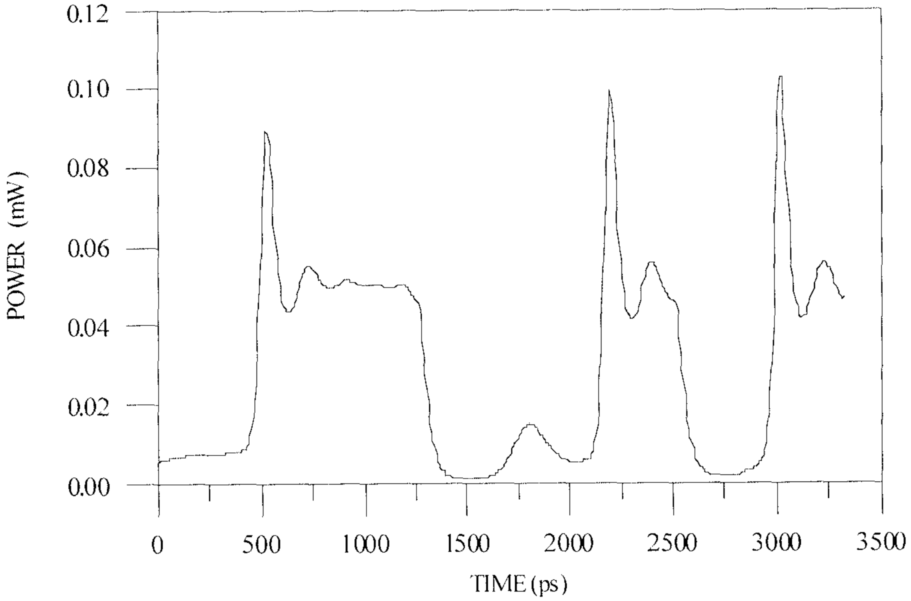

Fig. 2d: Fibre output power with Dg = -20 ps/km.nm, s = 0.2 dB/km and L = 50 km

The improvements promised by the pulse shaping in the current results place special requirements on the design of the practical systems if they are to be realized. First, the large excursions in the laser and fibre outputs are due to the shorter rise and fall times in the drive current pulses such as those shown in Fig. 2a. In the subsequent figures, however, the excursions have been reduced through employing pulses having longer rise and fall times. In practical systems therefore, the laser drive circuits are designed using special techniques so that they transform the square-shaped pulses of Fig. 2a into the trapezoidal-shaped ones of Fig. 5a. Secondly, when the sharp edges of the pulses are improved through filtering as shown in Fig. 3a, the laser and fibre outputs are improved. Extra design efforts are therefore applied to the laser drive circuits in order to impart a smoothening effect, similar to that shown in Fig. 3a, to the current pulses. The application of these design techniques provides current pulses that can be used in actual systems because the pulses are much smoother than those shown in Fig. 5a, and the signals at the fibre outputs have shapes that make them less susceptible to erroneous detection.

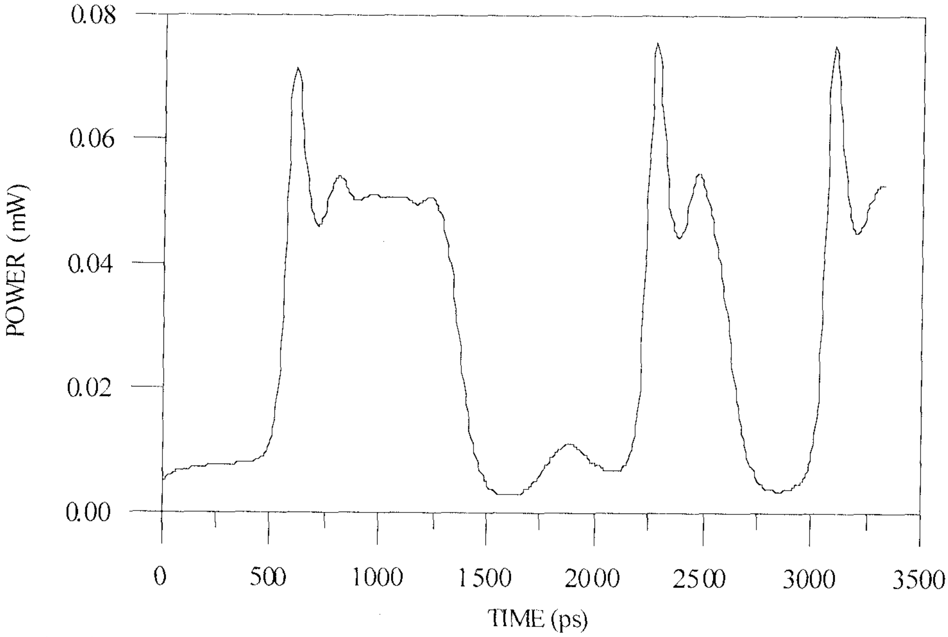

Fig. 3b: Fibre output power with Dg = -20 ps/km.nm, σ = 0.2 dB/km and L = 50 km

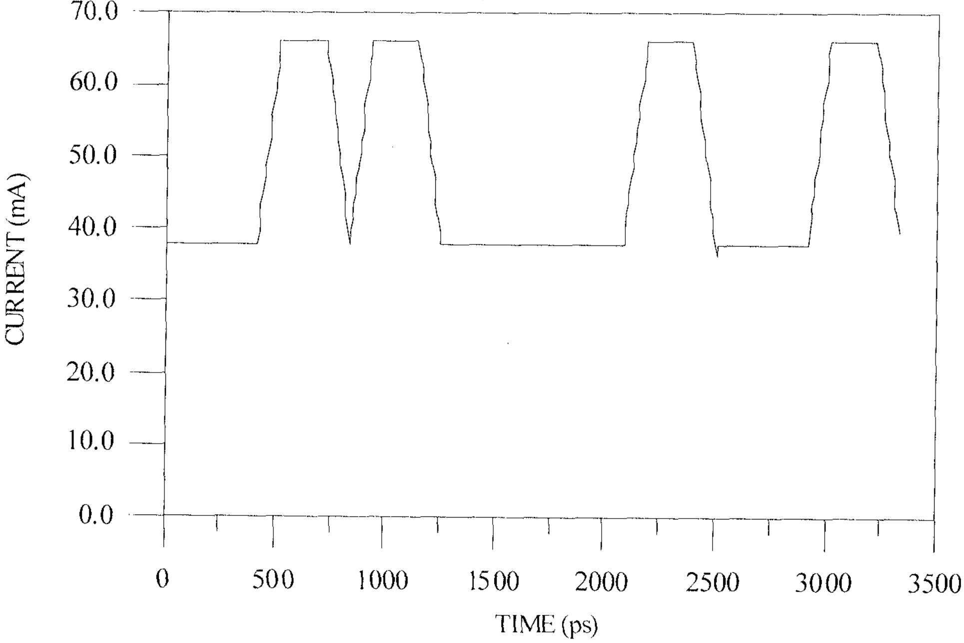

Fig. 4a: Laser drive current for bit sequence 01100101

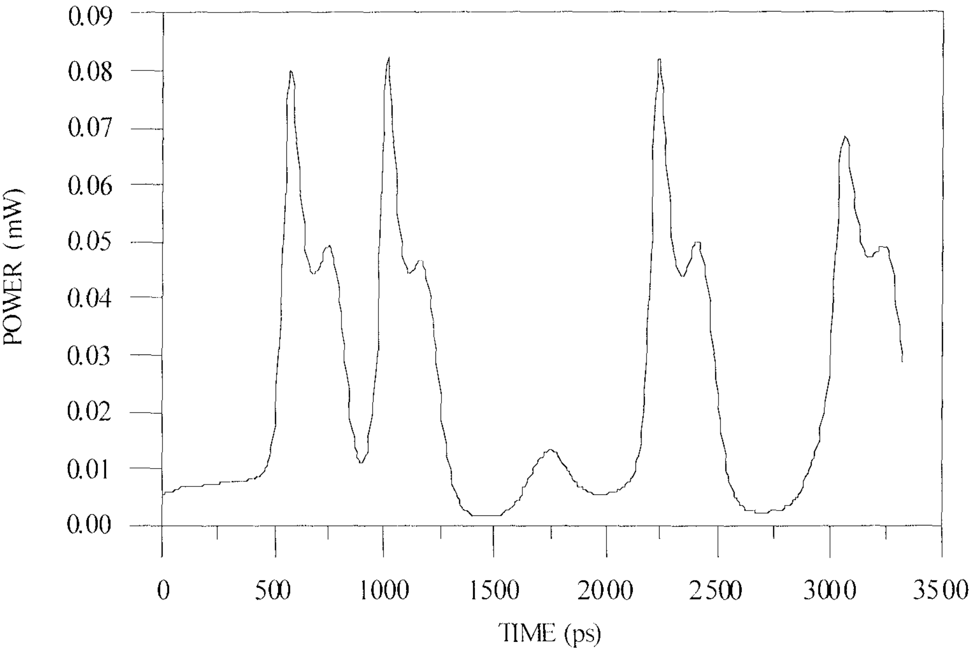

Fig. 4b: Fibre output power with Dg = -20 ps/km.nm, σ = 0.2 dB/km and L = 50 km.

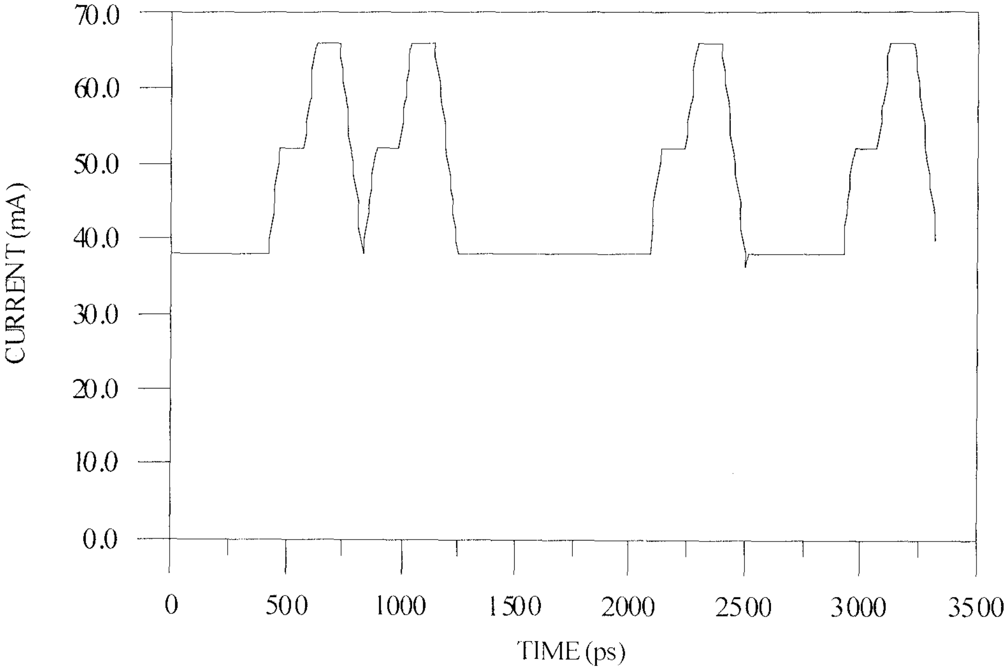

Figure 5a: Laser drive current for bit sequence 01100101

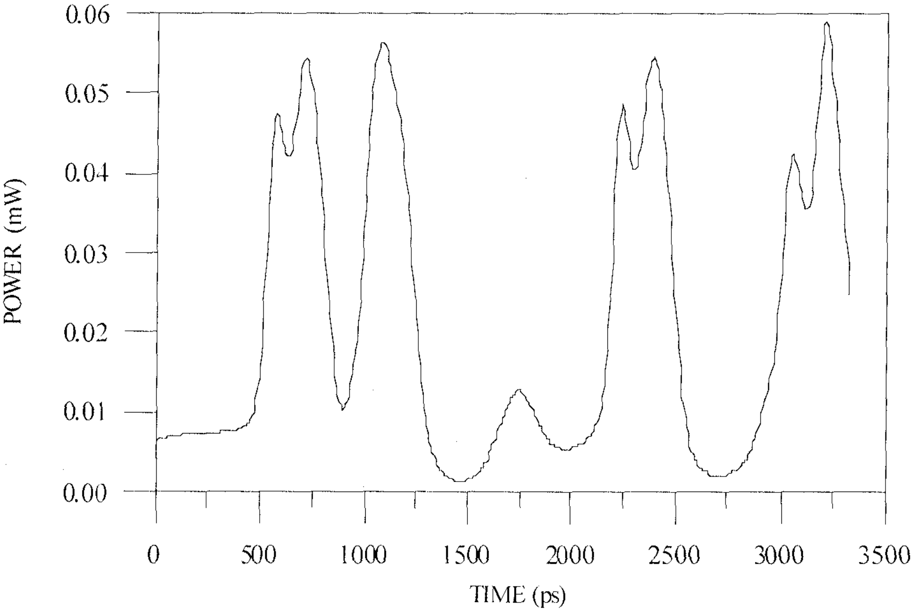

Figure 5b: Fibre output power with Dg = -20 ps/km.nm, σ = 0.2 dB/km and L = 50 km

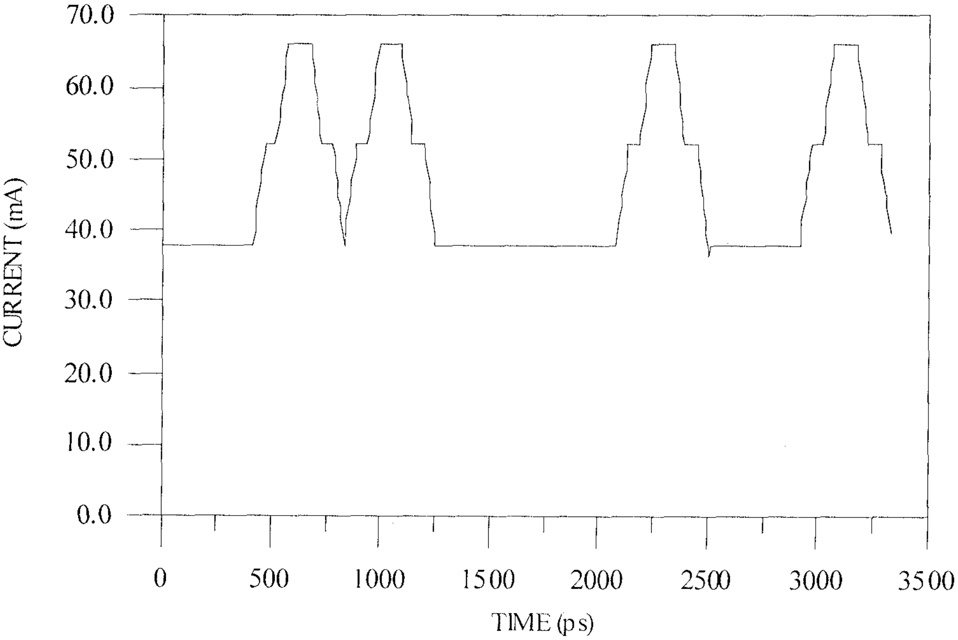

Fig. 6a: Fibre output power with Dg = -20 ps/km.nm, σ = 0.2 dB/km and L = 50 km

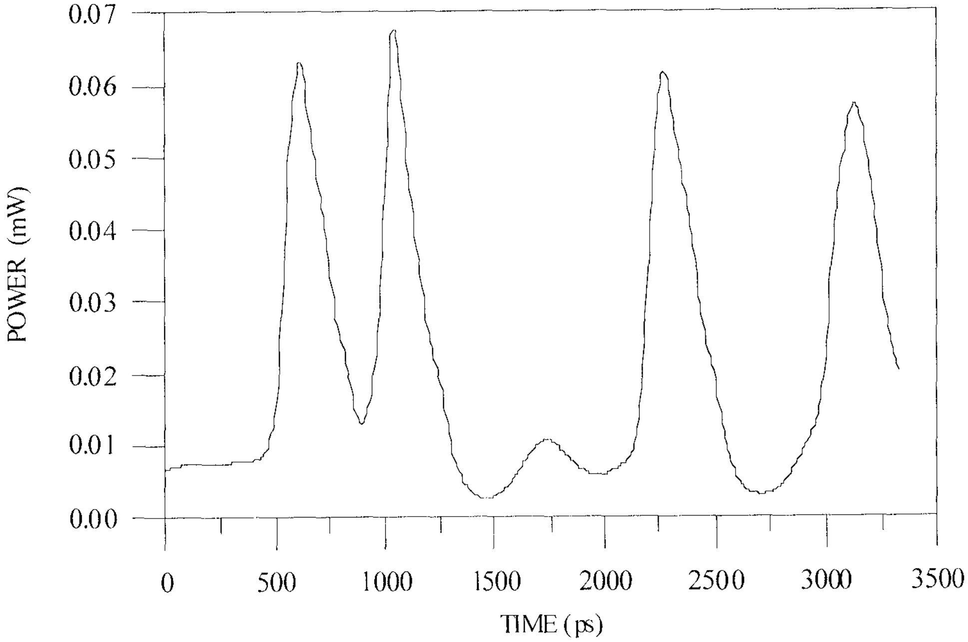

Fig. 6b: Fibre output power with Dg = -20 ps/km.nm, σ = 0.2 dB/km and L = 50 km

CONCLUSION

The analysis of an optical fibre-communication system up to the fibre output stage has been undertaken using the rate equation model of the laser and practical values of the fibre parameters. The laser output power, the laser output chirp and the fibre output power showed the same trend as that reported in other studies for both unfiltered and RC-filtered square-shaped pulses. The pulse shapes at the output of the fibre showed improvements as the input pulse shapes depart from the square to the less square ones. Among the pulse types used, the trapezoidal pulse with a pedestal on the leading edge gave the best shape at the fibre output. This pulse shape however, can not be claimed to be the best among all the possible shapes. In practical systems, special design techniques need to be applied to the laser drive circuits so that they produce trapezoidal shaped pulses. Such pulses are also smoothened to remove the sharp edges, and this lead to correct signal detection at the fibre outputs.

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