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Optimizing Transmission Capacity: Long Distance and Terrestrial Applications

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Optimizing transmission capacity: long distance and terrestrial applications

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This paper identifies the important limiting processes in transmission capacity for amplified soliton systems. Some novel control techniques are described for optimizing this capacity. In particular, dispersion compensation and phase conjugation are identified as offering good control of jitter without the need for many new components in the system. An advanced average soliton model is described and demonstrated to permit large amplifier spacing. The potential for solitons in high-dispersion land-based systems is discussed and results are presented showing 10 Gbit s^{-1} transmission over 1000 km with significant amplifier spacing.

1. Introduction

The advent of practical optical amplifiers has opened the prospect for installation of very long and high capacity optical communications systems (for a review of erbium-doped fibre amplifiers see Desurvire (1994)). The removal of loss as the limiting factor in optical systems restores to importance dispersion and nonlinearity as the limiting effects for such systems. Solitons are pulses wherein the nonlinearity (the nonlinear refractive index) and dispersion act in harmony and the pulses are not dispersive in either the temporal or frequency domain (for a review of soliton properties see Taylor (1992)). This paper will examine a range of approaches for utilizing solitons in amplified systems, both of intercontinental length and shorter land-based spans. The elimination of dispersion does not mean that there are no limiting effects; solitons bring with them their own series of effects which will limit the distance and data-carrying capacity. This paper will identify these processes, specify system limitations due to these effects and prescribe approaches to overcoming these by soliton control. It will emerge that the design of soliton systems will incorporate rather unique features which will permit an optimization of the data-carrying capacity of single-mode fibre systems.

2. Temporal optical solitons in fibres

In a single-mode fibre the dominant perturbations are loss, dispersion and nonlinearity. These three cannot generally be treated separately but we will start by ignoring the effect of loss. A pulse $u(t, z)$ in a single-mode fibre is subject to dispersion with dispersion coefficent β'' in $ps^2\ km^{-1}$, and, in a frame moving at the group

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velocity, its evolution can be simply described by

$$\mathrm{i}\frac{\partial u}{\partial z} - \tfrac{1}{2}\beta''\frac{\partial^2 u}{\partial t^2} = 0. \tag{2.1}$$

The pulse broadens and acquires a frequency 'chirp', the direction of which depends on the sign of β''. In single-mode fibres, either sign of β'' is possible around the operating wavelength of 1.5 µm.

The predominant nonlinearity in silica fibres is the intensity-dependent index $n = n_0 + n_2 I$, where $n_2 \sim 2.6 \times 10^{-16}\ \mathrm{cm^2\ W^{-1}}$. In a single-mode fibre with nonlinear area, A_{eff}, the propagation constant β is simply modified for a power P according to

$$\beta = \beta_0 + n_2 k \frac{P}{A_{\mathrm{eff}}}, \tag{2.2}$$

where k is the free space wavevector. For a pulse $u(t, z)$, a simple differential equation describes this nonlinear phase modulation:

$$-\mathrm{i}\frac{\partial u}{\partial z} = n_2 k \frac{|u|^2}{A_{\mathrm{eff}}} y, \tag{2.3}$$

with solution

$$u = u_0 \exp\left(\mathrm{i} n_2 k \frac{|u_0|^2}{A_{\mathrm{eff}}} z\right). \tag{2.4}$$

A time varying pulse, acquires a phase, ϕ, proportional to the local (in time) intensity and the distance travelled. This time-varying phase results in a local frequency $-\mathrm{d}\phi/\mathrm{d}t$ proportional to $\mathrm{d}|u|^2/\mathrm{d}t$. Thus, the pulse becomes chirped with low frequencies at the leading edge. The pulse is undistorted in the time domain but will broaden spectrally as the pulse travels. For a fibre of A_{eff} of 50 µm^2 at 1.5 µm, a π phase shift will occur for a power of ~ 1 W for 1 km. It is straightforward to include the effect of loss on this nonlinear propagation (dispersion is not included at this stage). The intensity follows the simple relation

$$|u|^2 = |u_0|^2 \mathrm{e}^{-2\gamma z}, \tag{2.5}$$

where 2γ is the loss in km^{-1}. The phase modulation for a distance z can be obtained by integration to give

$$u = u_0 \exp \mathrm{i}\left(\frac{n_2 k}{A_{\mathrm{eff}}}|u_0|^2\left[\frac{1-\mathrm{e}^{-2\gamma z}}{2\gamma}\right]\right), \tag{2.6}$$

i.e.

$$\phi = \frac{n_2 k}{A_{\mathrm{eff}}}|u_0|^2\left[\frac{1-\mathrm{e}^{-2\gamma z}}{2\gamma}\right].$$

From this we can define either an effective length or a path-average power such that the phase is proportional to the product of effective length with initial power, or average power with transmission length. Thus,

$$P_{\mathrm{av}} = \frac{P_0}{z}\left[\frac{1-\mathrm{e}^{-2\gamma z}}{2\gamma}\right], \tag{2.7}$$

or

$$z_{\mathrm{eff}} = \left[\frac{1-\mathrm{e}^{-2\gamma z}}{2\gamma}\right]. \tag{2.8}$$

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Returning now to the lossless case we can combine equations (2.3) and (2.1) to describe the propagation of a pulse $u(t, z)$ in the presence of dispersion and nonlinearity and write

$$\mathrm{i}\frac{\partial u}{\partial z} + \frac{k_2 n_2}{A_{\mathrm{eff}}}|u|^2 u - \frac{1}{2}\beta'' \frac{\partial^2 u}{\partial t^2} = 0. \tag{2.9}$$

Simply combining the separate effects of dispersion and nonlinearity into one equation adequately describes the propagation, but this is not proved here.

It is often more convenient to renormalize the variables in (2.9) and write the simpler version (β'' negative)

$$\mathrm{i}\frac{\partial u}{\partial z} + \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + |u|^2 u = 0. \tag{2.10}$$

Equation (2.10) is the nonlinear Schrödinger equation (NLSE), which has the following most important solution:

$$u(z, t) = 2\xi \mathrm{e}^{\mathrm{i}2\xi^2 z} \operatorname{sech} \xi t, \tag{2.11}$$

where ξ is an arbitrary constant.

These are the so-called soliton solutions. This pulse, which travels at the group velocity at the wavelength of interest, is undistorted on propagation in time and frequency. That is $|u(z, t)|$ and $|u(z, \omega)|$ are independent of z. This is the first and most notable soliton property. There are additional important soliton features. First, there is a uniform phase which is proportional to the normalized distance, i.e. $\phi_{\mathrm{sol}} = 2\xi^2 z$. The parameter ξ is arbitrary and shows that there is a continuum of solutions with a fixed relationship between peak amplitude and duration. We can now identify this relationship in 'real world' units. For a fibre with $A_{\mathrm{eff}} = 50\ \mu\mathrm{m}^2$, $\lambda = 1.5\ \mu\mathrm{m}$ and a dispersion D, the peak power $P = D/\tau^2$; the soliton phase

$$\phi_{\mathrm{sol}} = \tfrac{1}{4}\pi \times \frac{zD}{0.43 \times \tau^2}.$$

The soliton period, z_0, is taken conventionally to be when $\phi_{\mathrm{sol}} = \frac{1}{4}\pi$, i.e. $z_0 = 0.43\tau^2/D$ km. The existence of the continuum is the first indication of the most important property of solitons—stability. A perturbation to the motion—e.g. a discrete loss, a change of dispersion—may be simply accommodated by a slight alteration in the soliton parameters—e.g. loss would increase the width whilst decreasing the amplitude—but does not significantly disturb the soliton's identity. This also indicates that the initial-value problem can be simply expressed. If a pulse of imperfect shape or amplitude (width) is launched into the NLSE system, the soliton part will remain in time (and frequency) whilst the remaining energy will be discarded as a radiative wave.

We now turn to the important question of the effect of loss on solitons. Loss may be included into the NLSE by simply adding a term $-\mathrm{i}\gamma u$ on the left-hand side of equation (2.9). A perturbative, but not exact, solution is

$$u = \mathrm{e}^{-\gamma z} \exp\left(\mathrm{i}\left[\frac{1 - e^{-2\gamma z}}{2\gamma}\right]\right) \operatorname{sech}(t\mathrm{e}^{-\gamma z}). \tag{2.12}$$

The initial soliton remains a soliton but with increasing width and modified phase. In fact, the phase progress modification is exactly as in the lossy form for phase modulation, expressed in equation (2.6). The coefficient γ can express gain (distributed) if the sign is reversed in (2.12), and then the pulse is compressed and the phase progress accelerates.

The next important property of solitons is their interaction. Solitons of different frequencies will have different group velocities and can 'pass through' each other without exchanging energy. Solitons of the same frequency have zero relative velocity but do interact if they are close (in time). Two solitons separated in time by 2Δ of the same amplitude (and width) are observed to display periodic collapse re-emergence, if they are initially in phase, with period $z_c = \frac{1}{2}\pi e^{\Delta}$ (Chu & Desem 1983; Blow & Doran 1983; Gordon 1983). If $\Delta = 0$, the period is $\frac{1}{2}\pi$, and this is known as the soliton period z_0. The interaction depends on the relative phases of the two solitons and is repulsive for out-of-phase solitons. This interaction shows that solitons need to be well separated in time in order to maintain their integrity. Indeed, soliton systems are strongly RZ (Return to Zero) in that the mark-to-space ratio should be small, typically 1 : 5 to 1 : 10.

3. Amplified soliton systems

(a) Long distance systems

We shall now turn to a practical consideration of the operating designs for soliton systems over intercontinental distances. Discrete amplifiers may be used to restore periodically the soliton power. This periodic restoration of power will permit undistorted soliton transmission provided two conditions are met. First, the amplifier spacing must be somewhat less than the soliton period and second, the initial power is chosen so that the accumulated phase shift, as in equation (2.12), is equal to that which a lossless soliton would experience over the same distance. This is known as the average soliton prescription since it requires that the average power over a link is equal to the lossless soliton power, and thus the initial launched power must be greater than the soliton required power (Blow & Doran 1991; Hasegawa & Kodama 1990). Simply expressed, $P_{\text{in}} = P_0 \times \Lambda$, where P_0 is the lossless power and

$$\Lambda = \left[\frac{2\gamma z}{1 - \mathrm{e}^{-2\gamma z}}\right].$$

The next effect of amplifiers is to introduce noise. This has two important consequences for soliton systems. First, sufficient signal power must be launched to maintain the signal-to-noise ratio (SNR) for the error rate required. Solitons have fixed power, which depends on fibre dispersion and pulse duration, and thus shorter pulses may be needed to increase signal power. Second, the noise induces timing jitter. At each amplifier, the noise induces small random changes in the soliton's parameters—position, frequency, amplitude and phase. The most significant change is in the soliton's frequency and the soliton performs a random walk in time through the amplifier chain as a consequence of the fibre dispersion. This effect is known as Gordon–Haus jitter (Gordon & Haus 1986) and, in contrast to the background amplified spontaneous emission (ASE), becomes worse for shorter pulses. The timing variance grows cubically with distance and so eventually the probability that a pulse wanders into an adjacent bit period becomes unacceptable. We can thus define a lower limit on the pulse width in terms of the variance σ acceptable for a system of

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total length L:

$$\tau \geqslant \frac{1}{\sigma_{\text{sig}} \max} \frac{1}{9} \frac{1.76}{A^2} (G-1) \eta_{\text{sp}} \frac{Dhn_2}{z_{\text{a}} A_{\text{eff}}} L^3, \tag{3.1}$$

here η_{sp} is the amplifier spontaneous emission factor, z_{a} is the amplifier spacing (km), A_{eff} is the effective area of the mode and G is the gain in an individual amplifier.

We now identify the four primary constraints on soliton system design. These are as follows.

(i) Gordon–Haus jitter (GH).
(ii) SNR-requirements (SNR).
(iii) Soliton–soliton interaction (SS).
(iv) Average soliton limits (AS).

The first constraint is defined above in equation (3.1). For (ii) we will make it a condition that the SNR is acceptable for the error rate. Here we shall take an SNR of 23 dB, which allows a 4 dB margin for the bit-error ratio (BER) of 10^{-12}. We can derive a complex but straightforward expression for the pulse duration in terms of the amplifier spacing in terms of the SNR:

$$\tau < 1.76 A^2 R \ddot{\beta} \left(\frac{c A_{\text{eff}}}{n_2 \omega_0} \right) 10^{-\text{SNR}/10} \left(\frac{z_{\text{a}}}{L} \right) \frac{1}{Bh\nu\eta} (G-1), \tag{3.2}$$

where R is the bit interval, B is the bandwidth of the receiver and L is the amplitude of the launched pulse in normalized units.

For condition (iii) we shall take a system length maximum of half the collapse length, i.e.

$$L < \tfrac{1}{4} z_0 \exp(\Delta/\tau). \tag{3.3}$$

The final constraint comes from average soliton considerations and we take the limit that $z_{\text{a}} < \frac{8}{10} z_0$, i.e.

$$z_{\text{a}} < \tfrac{8}{10} (\pi \tau^2 / 2\ddot{\beta}). \tag{3.4}$$

We are now in a position to construct design diagrams for soliton systems. The parameters which can be designed around are pulse duration, amplifier spacing and dispersion. We shall plot pulse duration against amplifiers spacing for various fibre dispersion values. Figure 1 shows design diagrams for two lengths of system (10 000 and 6500 km), corresponding to transpacific and transatlantic distances. The limit imposed by GH and AS define lower pulse duration limits, SNR and SS define upper pulse-duration limits. The diagrams show that in these uncontrolled systems, 2.5 Gbit s^{-1} can be safely transmitted for both distances for amplifier spacing of around 40 km. However, there is no region of operation at 5 Gbit s^{-1} for 10 000 km. 10 Gbit s^{-1} is not possible for either distance and is only illustrated for the shorter length in figure 2.

(i) *Soliton control*

It is clear from the design diagrams that in order to operate with solitons at 5 Gbit s^{-1} or more, some reduction in the jitter, in particular, is necessary. There are a large number of proposals for controlling solitons in order to reduce jitter and the interaction. The best known of these is probably through the use of bandpass filters. These control the soliton's frequency and, thus, in turn the jitter in time. If a filter is introduced at each amplifier stage, the standard deviation may be reduced by $\sim 50\%$ before increased ASE limits the effect (Mecozzi *et al.* 1991). A particularly elegant

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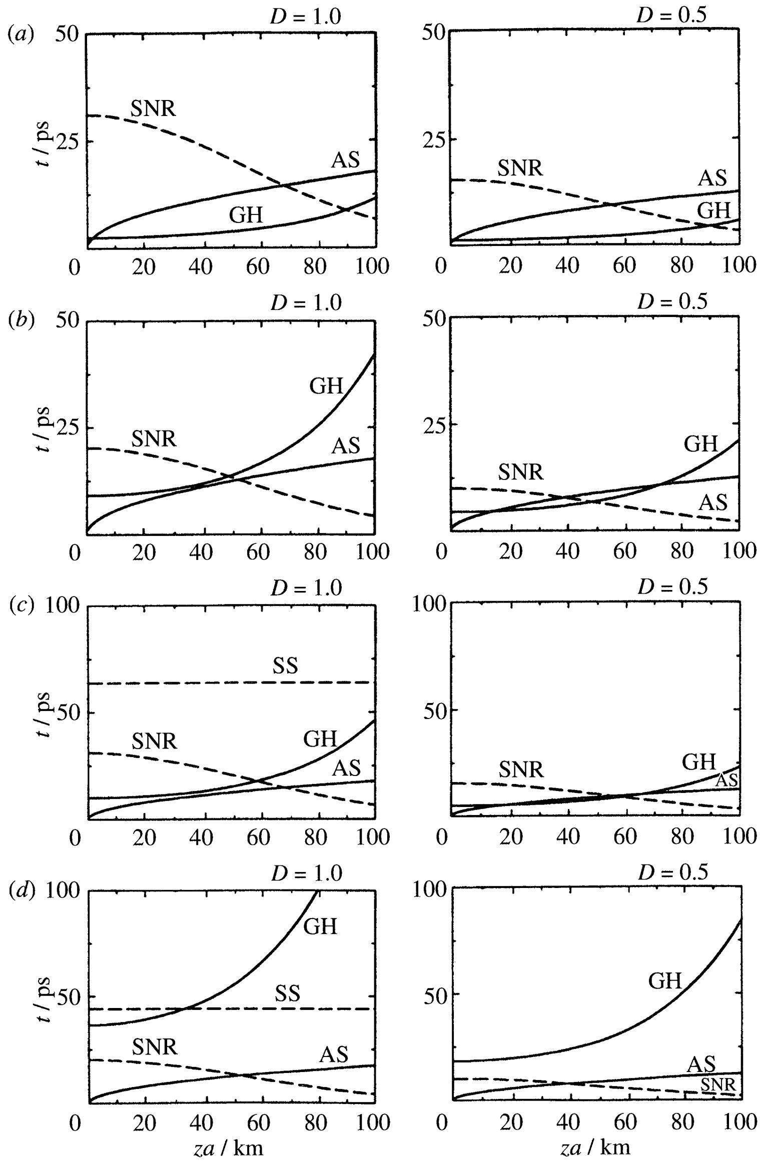

Figure 1. Design diagrams (pulse duration versus amplifier spacing) for uncontrolled soliton systems: (*a*) $L = 6.5$ Mm, $R = 2.5$ Gbit s^{-1}; (*b*) $L = 10$ Mm, $R = 2.5$ Gbit s^{-1}; (*c*) $L = 6.5$ Mm, $R = 5$ Gbit s^{-1}; (*d*) $L = 10$ Mm, $R = 5$ Gbit s^{-1}. The full lines represent minimum pulse width and the dashed lines maximum pulse width: AS, average soliton limit; SS, soliton–soliton interaction; GH, Gordon–Haus limit; SNR, signal-to-noise ratio limit.

solution to this limit is to slide the central frequency of the filter progressively across the system (Mollenauer *et al.* 1992). Much greater filtering may then be employed and jitter greatly reduced. This sliding guiding filter is extremely effective but does require specified new components at each amplifier in the chain; there are other alternative approaches which may be simpler to implement and we shall concentrate here on some of these alternative strategies.

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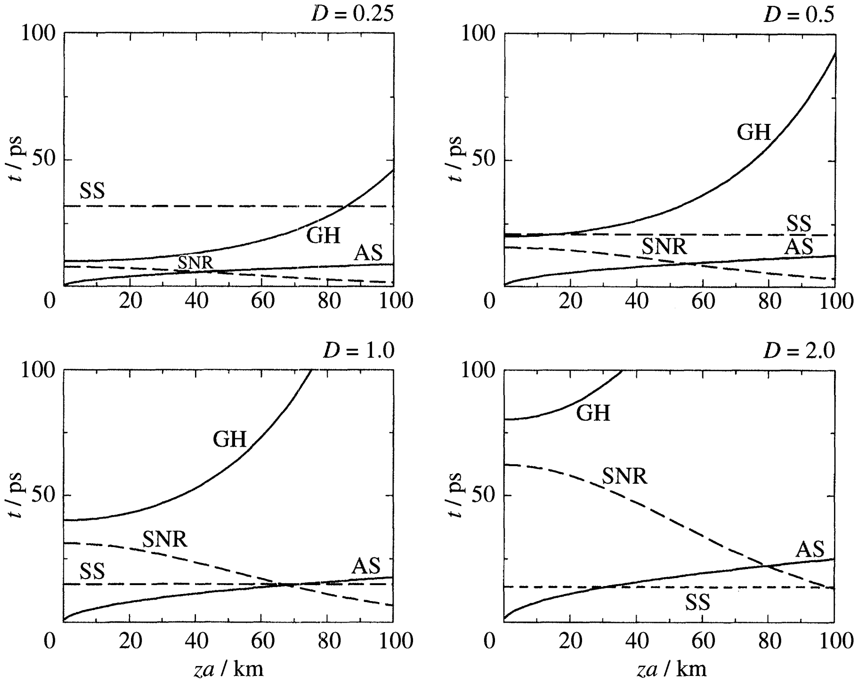

Figure 2. Design as in figure 1 for $L = 6.5$ Mm, $R = 10$ Gbit s^{-1}.

(ii) *Dispersion compensation*

The jitter occurs as a consequence of the amplifier noise-induced frequency jitter, which is translated into timing jitter via dispersion. We may write a simple expression for the timing variance after N amplifiers z_a apart:

$$\langle \Delta t^2 \rangle = \sum_{j=1}^{N} (\ddot{\beta} j z_\mathrm{a})^2 \langle \delta\omega^2 \rangle. \tag{3.5}$$

It is interesting to note that the timing jitter may be reduced significantly by employing a post-transmission dispersion-compensating element. Simply, if dispersion equal to half of the total transmission dispersion is added, the variance is reduced to a quarter of its uncompensated value. Such a reduction effectively doubles the data-rate limit in the above design diagrams (Forysiak *et al.* 1993). Thus 5 Gbit s^{-1} becomes possible for 10 000 km and 10 Gbit s^{-1} is possible for 6500 km. In addition, this compensation approach may be added to a filtered system reducing further the jitter. This simple technique has not yet been applied to practical systems but could enable 5 Gbit s^{-1} systems of comparable simplicity to 'non-return-to-zero' (NRZ) links, but with a realistic prospect for upgrading through multiplexing.

A related approach, which may be used to invert dispersion effects, is phase conjugation. If, at the mid-point of the system, the phase conjugate is generated and that new signal propagated in the second half, then all the NLSE propagation effects are reversed (Forysiak & Doran 1994). In addition, the timing jitter is reduced in an identical way to the dispersion-compensation scheme. Thus, soliton interaction and jitter may both be significantly reduced by this technique. The scheme does, however, require a mid-point nonlinear element and thus may be undesirable. However, just one such element is needed and the element may not require clock recovery and can be, in principle, data-rate independent.

(iii) *Soliton multiplexing*

Solitons of different wavelength do not interact so that, in principle, it should be possible to transmit several soliton wavelength channels simultaneously. There are, however, additional dimensions available to solitons. First, polarization multiplexing may be employed since solitons will undergo polarization rotation as a unit and two orthogonally polarized solitons will retain that orthogonality along the fibre even though there are random fluctuations in birefringence along the fibre. Second, amplitude may be used as a multiplexing dimension. Solitons with different amplitudes have a different rate of phase change. Consider two solitons with parameters ξ_1 and ξ_2 as in equation (2.11). The collapse period is $z_c = \frac{1}{2}\pi e^{\Delta}$ where 2Δ is the separation. If we require that the relative phase of the solitons is $\frac{1}{2}\pi$ after a collapse length, then collapse will be avoided, i.e.

$$(2\xi_1^2 - 2\xi_2^2)z_c \geqslant \tfrac{1}{2}\pi, \quad 2(\xi_1+\xi_2)(\xi_1-\xi_2) \times \tfrac{1}{2}\pi e^{-\Delta} \geqslant \tfrac{1}{2}\pi. \tag{3.6}$$

Thus, taking $\xi_1 + \xi_2 = 1$ (i.e. the difference is around $\xi = \frac{1}{2}$) and $\Delta = 3$,

$$\xi_1 - \xi_2 = 0.025. \tag{3.7}$$

Thus, a 5% difference in amplitude will ensure no collapse for solitons with separation of $\Delta = 3$. In this case, the soliton separation is thus

$$\frac{2 \times 3}{1.76}\tau,$$

where τ is the FWHM width. Thus, a mark-to-space ratio of 1 : 3.4 is possible provided the solitons are modulated by 5% in amplitude. This approach is often called alternating amplitude, although in fact the modulation may be over several pulses.

Thus, solitons may be multiplexed in up to four dimensions, polarization, amplitude, wavelength and time. This multidimensionality may make solitons particularly attractive for all-optical networks, where routing may be performed by one of these dimensions.

(iv) *Phase-modulation control of solitons*

We turn now to the concept of active control of solitons. The active control considered here is phase modulation synchronized to the data rate at some intermediate stage in the system.

If we consider the case of a single such modulator at, or close to, the mid-point of the system, we can, from simple analysis, derive an expression for the optimized modulator strength to minimize the jitter (Smith *et al.* 1994):

$$\tfrac{1}{2}\Phi_m \omega_m^2 = \frac{5}{4\ddot{\beta}L}, \tag{3.8}$$

where Φ_m is the peak phase modulation, ω_m is the frequency of modulation and L is the system length. The modulation reduces the jitter variance by a factor of five and will thus effectively double the data rate possible for any transmission link. The phase modulation may be imposed by all-optical means or by electro-optical modulation. The combination of phase modulation with dispersion compensation—post transmission—will reduce still further the jitter. Calculation shows that the reduction may reduce the jitter variance by a factor of seven or more.

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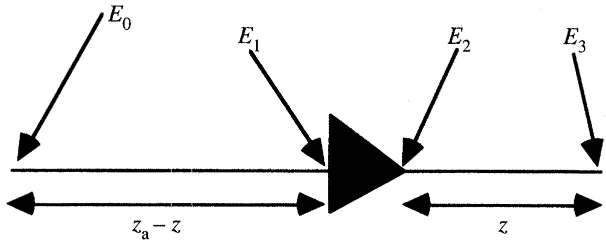

Figure 3. The unit cell with amplifier at position z relative to origin.

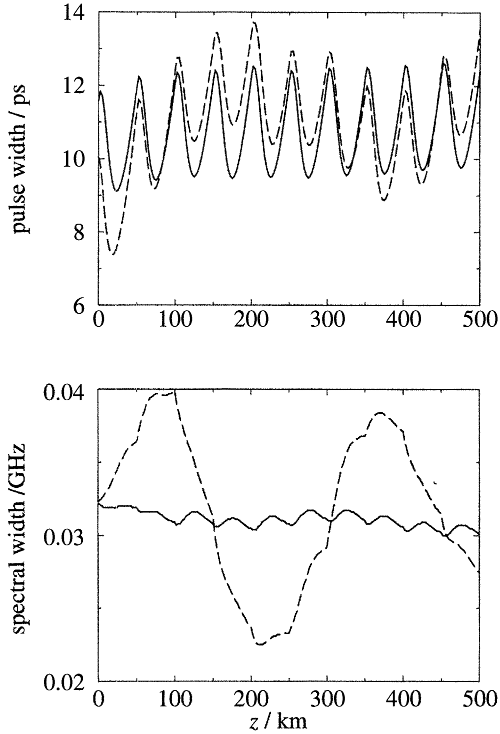

Figure 4. Temporal and spectral width variation for advanced average soliton (full curve) compared with standard model (dashed curve): ($z_a = 50$ km, $D = 1$ ps nm^{-1} km^{-1}, $t = 10$ ps).

(b) Solitons in land-based systems

(i) Improved average-soliton model

We shall now present an improved approach to the design of periodically amplified soliton systems. This approach will be particularly significant in shorter systems, which will probably be land based. The average-soliton principle, identified and utilized in the design diagrams above, takes no account of pulse-shape variations between amplifiers. However, as the amplifier spacing is increased to approach the soliton period the perturbations due to the system periodicity become increasingly evident. Here we extend the principle to include the possibility of pulse-shape changes between amplifiers. The approach we take is to assume a sech(t) pulse source and optimize the position of the first amplifier in the periodic chain. Figure 3 illustrates this approach. We can calculate the error over a unit cell defined as in the diagram and minimize this by choosing an optimizing position for the amplifier. The

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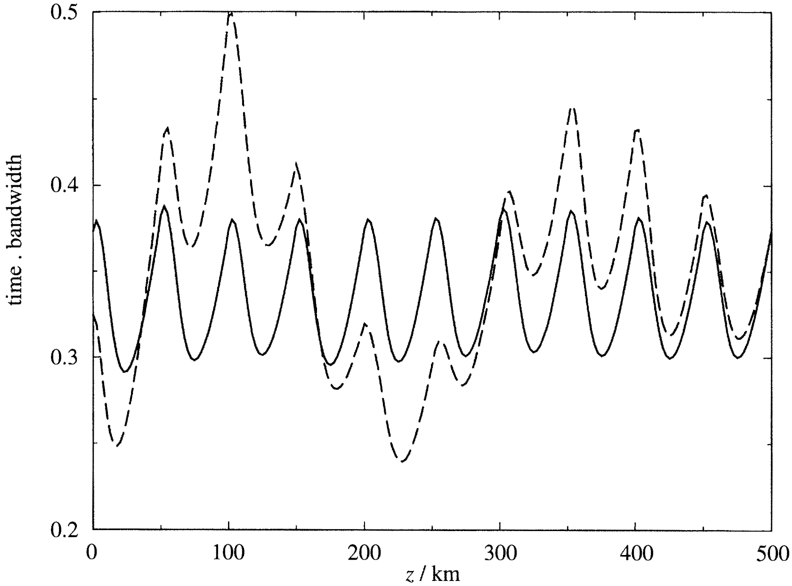

Figure 5. Variation in time bandwidth product of pulse as in figure 4.

analysis is presented in detail in Forysiak *et al.* (1995) but simply concludes that the minimum error occurs for positioning of the amplifier at position z, given by the solution to

$$\frac{1}{2\gamma} + \frac{z_{\mathrm{a}}}{z} - z - \frac{z_0 \mathrm{e}^{-2\gamma z}}{1 - \mathrm{e}^{-2\gamma a_{\mathrm{a}}}} = 0, \tag{3.9}$$

where γ is the loss coefficient and z_{a} is the amplifier spacing. There are two solutions of equation (3.9) representing optimum positioning of the initial amplifier. This result applies to all soliton systems but is only significant when the amplifier spacing approaches the soliton period. Figures 4 and 5 show results of calculations based on this advanced principle compared with the conventional average soliton. In this example, we take an amplifier spacing of 50 km, $D = 1\ \mathrm{ps\,nm^{-1}\,km^{-1}}$ and a pulse duration of 10 ps. The soliton period at 39.6 km is somewhat less than the amplifier spacing. In figure 4 we show the pulse-width variation over 10 amplifier spacings; for comparison, we also show the variation of pulse width for the conventional approach. Figure 4 also shows the spectral variation. It is clearly shown that this new prescription results in more stable propagation in both dimensions. Figure 6 shows the initial pulse evolutions for the two prescriptions, again the advanced average soliton approach shows very clear improved stability.

These calculations are based on single pulses and do not attempt to translate these results into a complete system design. The usefulness of the approach is particularly relevant for comparatively short spans of a few tens of amplifiers in the chain. Data rates of 20–40 Gbit s^{-1} could be envisaged for such distances using the parameters used in this present calculation with large amplifier spacing. It is the latter benefit which this approach provides.

(ii) *Solitons in high-dispersion fibre systems*

Of the 50 million kilometres of optical fibre installed worldwide, most is optimized for operation at 1.3 mm, using electronic regenerators to maintain the data. The most

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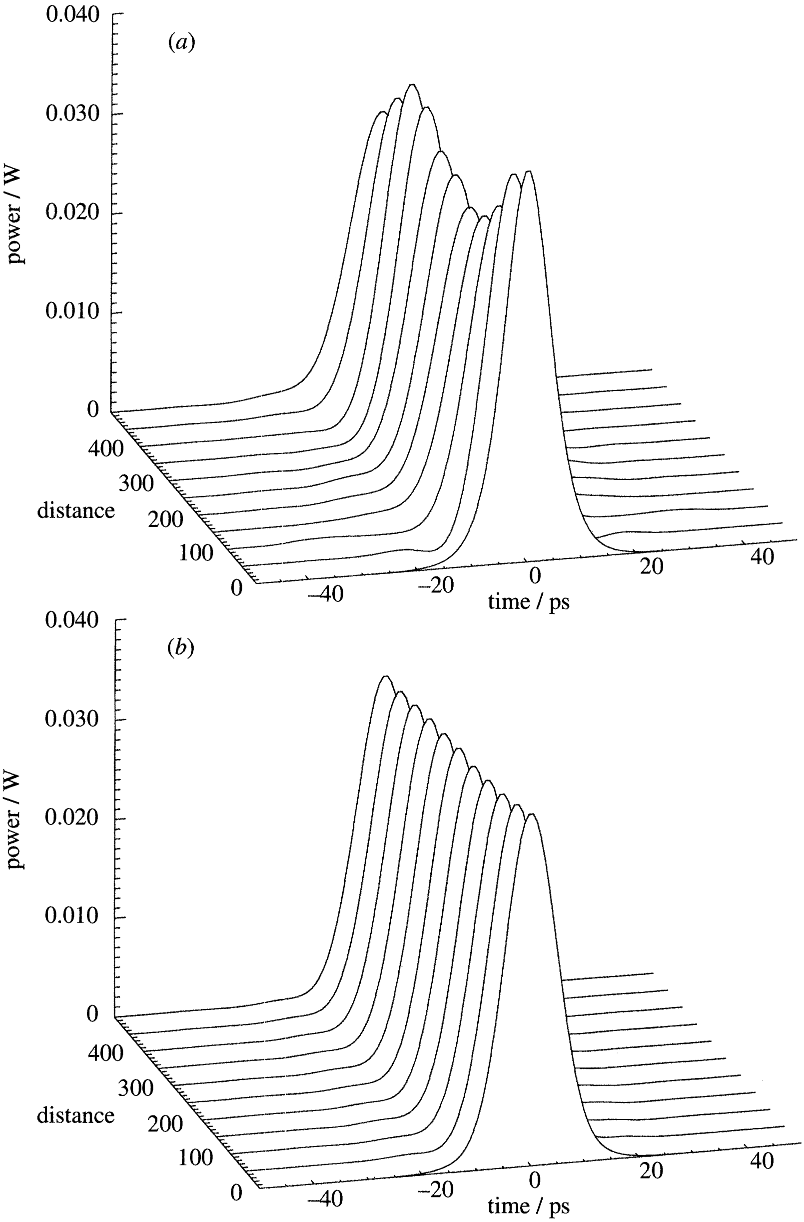

Figure 6. Initial pulse evolution at each amplifier for (*a*) advanced average soliton and (*b*) standard model.

readily available amplifiers operate at 1.5 μm. Thus, it is important to investigate whether solitons offer useful potential for dispersion compensation in such systems. Here we shall consider the particular problems in using solitons to upgrade standard fibre systems with EDFAs to 10 Gbit s^{-1} for amplifier spacings of 36 km, which is a specific but important technological challenge relevant to the current European optical network. We anticipate that the total system length will be no more than 1000 km.

Of the design constraints identified in § 3 *a*, the timing jitter and the required output SNR are not the important considerations in such short systems. The average soliton and soliton–soliton interaction constraints play the most significant role. The optical power required to support soliton propagation is also important for standard fibre systems since the average optical power P_{av} is proportional to the dispersion. While EDFAS can be designed to give sufficient gain and signal output power, unduly large optical powers are undesirable as they may lead to a reduction in amplifier lifetime, higher-order nonlinear effects and for safety considerations. The actual power requirement of the system is set by the average soliton condition. Here we assume that the EDFAS can provide the optical powers and gain necessary for soliton propagation, with the amplifier output power in the range 5–15 mW and gain of around 8 dB.

The standard fibre used here is taken to have a dispersion of 15 ps nm^{-1} km^{-1} and a loss of 0.2 dB km^{-1}. Using the criteria developed in § 3 *a*, there is an acceptable region of operation for a 144 km system with 10 mW optical power output from the amplifiers at separations below 12 km with pulse widths around 25 ps. For system lengths of 360 km or more, the constraints dictate higher average powers of 15 mW, shorter pulse widths of around 15 ps and impractically short amplifier spacings below 6 km. However, these design rules are based on long-haul system considerations with conservative guidelines. Therefore, in order to identify the limits more precisely, we have performed extensive sets of numerical simulations using full NLSE propagation (further details of these calculations may be found in Knox (1994, 1995)).

The system was simulated by propagating a random sequence of 144 data bits, 50% data 'ones', via the split-step Fourier method. Amplification by gain equal to the previous loss included ASE noise for an amplifier inversion factor $\mu = 1.4$. An estimate of the BER was found from the received filtered eye diagrams through the Q-parameter method. For each BER computation, nine sets of 16 bits were propagated for speed of simulation, as this gave similar results as for a single 144 bit propagation.

The calculations we performed for a range of pulse widths from 10–50 ps for up to 360 km to determine the maximum transmission distance. We now set the amplifier spacing at 36 km, after only a few amplifications the pulse train will begin to distort; however, the energy associated with each data 'one' largely remained in the appropriate bit slots. The simulations show that the data could still be recovered to a distance of 216 km. This was found to be the case for pulse widths between 25 and 35 ps. For a shorter system of length 144 km, data streams of pulse widths 22–38 ps propagated with acceptable error rates. As the total transmission distance increased, so the range of pulse widths diminished. However, this is substantially better performance than anticipated by the design diagrams.

In these simulations, the initial conditions were taken for in-phase solitons of equal amplitude. It has been suggested that using pulses in antiphase (π difference between bits) or phase quadrature ($\frac{1}{2}\pi$ difference), or that alternating the amplitudes to adjacent bits could, in principle, remove soliton interactions and thus constitute the most stable operation. Examination of all possible phase differences, or up to 10% amplitude variations, showed a degradation in the BER. The close proximity of adjacent solitons in neighbouring bit periods and the relatively large phase evolution per amplifier period is seen to give significantly different soliton dynamics to that observed in lightly perturbed cases.

In order to alleviate the constraints on soliton propagation for this system we considered reducing the *average* dispersion by dispersion compensation. There are several methods of dispersion compensation available, including optical-fibre Bragg

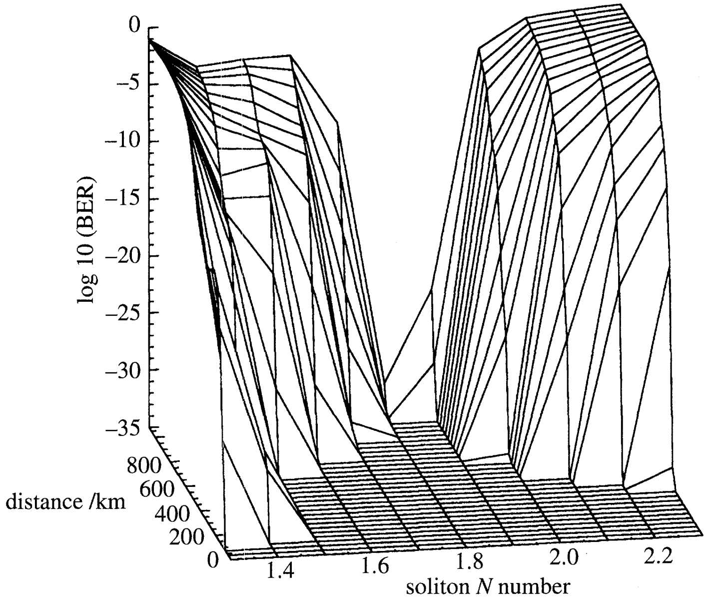

Figure 7. BER against distance and initial N number for a 10 Gbit soliton system over standard fibre with dispersion compensation to 5 ps nm^{-1} km^{-1}, 36 km amplifier spacing.

gratings. Here we studied the use of dispersion-compensating fibre (DCF), which is commercially available and has high negative group-delay dispersion in the 1.55 μm region. By incorporating a length of this fibre before the active fibre as part of each amplifier node, the average dispersion, and thus the perturbations of each amplifier link, should be reduced. The extra fibre is considered part of the amplifier, not an addition to the system length. The actual DCF simulated was not of the optimum dispersion and loss, but taken as −50 ps nm^{-1} km^{-1} and 0.2 dB km^{-1}, respectively (although DCF usually has higher loss). The additional fibre must be placed in the dispersion-dominant part of the soliton evolution, before the amplifier gain rather than after it, as this introduces even greater perturbations than having no DCF. It is worth keeping in mind that along with these improvements to propagation fidelity, the average power required to support solitons is reduced proportionally with decreasing dispersion.

Again, simulations were carried out to test the design diagrams found for pulse widths of 5–45 ps over the range of average dispersions from 1–15 ps nm^{-1} km^{-1}. Although there are still perturbations and distortions, the pulse integrity improves as the dispersion is reduced towards 6 ps nm^{-1} km^{-1}, where the data can be recovered for whole 360 km system length, or, for 144 km, the range of pulse widths increases to 10–40 ps.

Below 6 ps nm^{-1} km^{-1}, the results become somewhat unpredictable, as the perturbations due to the additional fibre length become significant. Oscillations are found where the error rate degrades and then recovers. This is thought to be due to soliton interactions. It was found that increasing the input optical power can give improved and longer transmission distances. Figure 7 shows the variation found in the BER with distance for input solitons of $N = 1.30$–2.30, where the average soliton model gives a value of $N = 1.51$. As can be seen, for $N \approx 1.85$ the 20 ps solitons used in these simulations can propagate for 1080 km before error are observed. One possi-

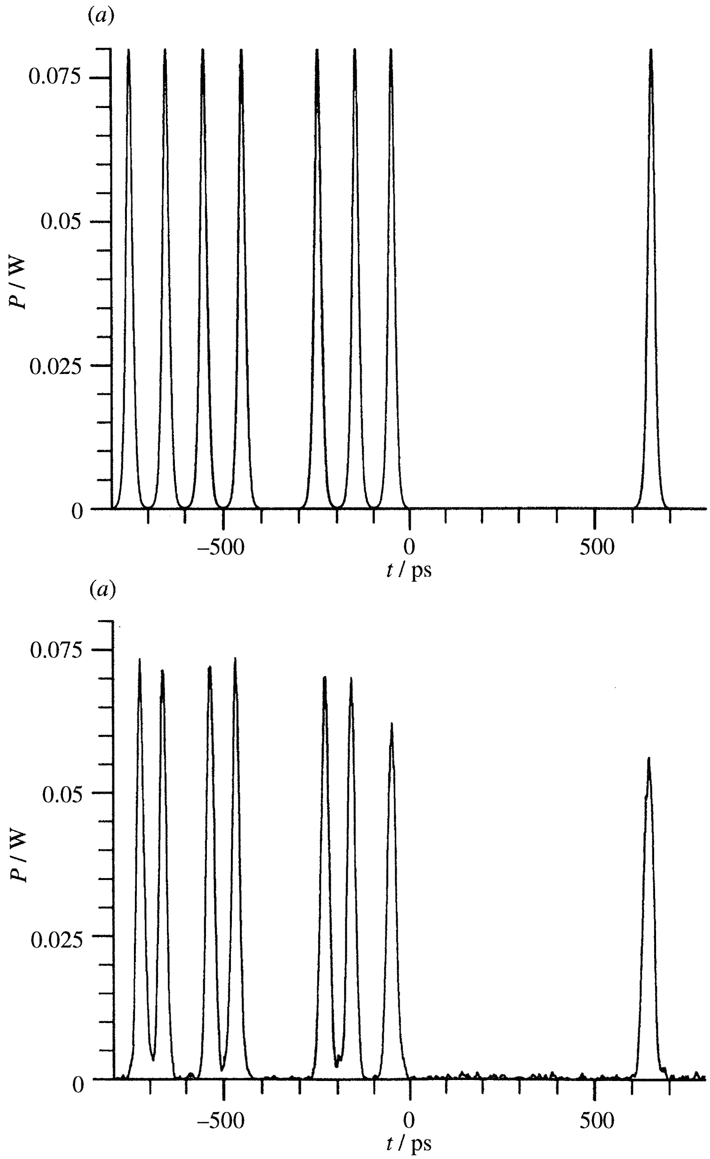

Figure 8. Pulse train evolution to 1000 km for launch corresponding to $N = 1.8$ as in figure 6: (*a*) initial pulse train; (*b*) final pulse train.

ble explaination of this effect is that the pulses at this point are not true solitons, as input, but somewhat chirped in steady-state propagation. Increasing the input power provides the required energy for these near-solitons to evolve to the steady state. Figure 8 shows the evolution of a pulse train showing clear stability out to a distance greater than 1000 km. We note that if the average soliton prescription had been followed, the evolution would not have extended beyond 500 km.

In conclusion, we have shown that it is possible to upgrade short standard fibre systems to 10 Gbit s^{-1} using erbium-doped fibre amplifiers and solitons. Despite the fact that the perturbations to the solitons are large, error-free operation is possible to around 200 km using relatively long 36 km amplifier spacings and optical powers of 12 mW. The best operation is obtained for solitons which are initially in phase and of equal amplitude. By introducing a section of DCF immediately before each amplifier, the average dispersion, and hence pertubations, can be reduced. Reduction of the dispersion in this manner to 5.0 ps nm^{-1} km^{-1} increases the total transmission distance to in excess of 360 km, extends the tolerable pulse widths from 25–35 ps to 10–40 ps for the 144 km system, and reduces the average power requirement to 5 mW. We have shown propagation in excess of 1000 km by using enhanced initial soliton power beyond that predicted from the single average soliton principle for average dispersion of 5 ps nm^{-1} km^{-1}.

4. Conclusion

This paper has identified potential applications for solitons in high-data-rate amplified systems. By using a single-phase modulator, in combination with a degree of dispersion compensation, 10 Gbit s^{-1} for 10 Mm should be possible on a single channel without the need for filter control. This system could be multiplexed, but would require separate modulation for each channel. Data rates of 40 Gbit s^{-1} should then be possible.

For shorter land-based systems, solitons have significant potential although they will require a degree of dispersion compensation if high-dispersion transmission fibre is used.

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