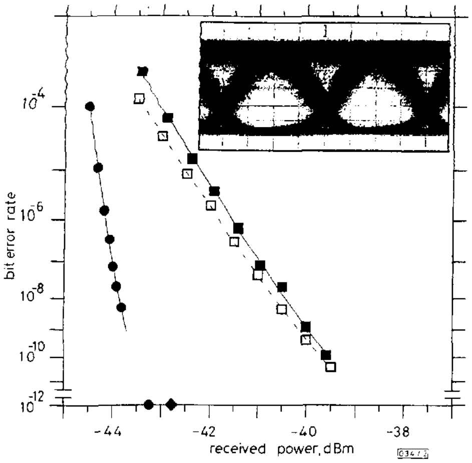

Fig. 2 *BER against received power*

- ■ measured BER against received power at remote preamplifier without FEC
- □ measured BER without booster amplifier SBS suppression DCF or FEC
- ● measured BER for 519.2 km system with FEC
- ● error-free performance (BER < 10^{-12}) of 529. 1km system with FEC

The pump power is 1.3W, of which 6.1dBm reaches the EDF segment. With a pump reflector (a fibre grating), the gain is 18.2dB. The measured bit error rate performance is given in Fig. 2 with the abscissa of the chart being the received power at the front of the remotely located preamplifier; i.e. to the immediate left of the pump reflector in Fig. 1. The received power required for a bit error rate of 10^{-9} is –40.0dBm. In Fig. 2, the insert shows the eye-pattern for a bit error rate of 1.2×10^{10}. The open squares indicate the bit error rate performance when the data-encoded signal from the modulator is injected into the remotely pumped preamplifier via 31km of DCF to compensate for the dispersion of the 118km receiver fibre segment. Furthermore, the receiver does not include dispersion compensation in this case. The data show that a power penalty of only 0.2dB is observed from dispersion compensation, phase modulation for SBS suppression, and self-phase modulation due to the high launch power.

The addition of forward error correction coding using a 255/239/8 Reed Solomon code improves the performance. The solid circles in Fig. 2 show the bit error rate (BER) as a function of the received power at the remote preamplifier with a total transmission distance of 519.2km and 92.9dB of fibre loss. A received power of > –43.7dBm ensures error rates < $10^{-9}$and at a received power of –43.25dBm, the system is experimentally confirmed to be error free; i.e. $BER < 10^{12}$. The bit error rate curve is, as expected from theoretical predictions, very steep. The BER increases from 10^{-9} to 10^{-4} for a decrease in received power of only 0.8dB.

By changing the receiver fibre segment to a 123.0km fibre span with 21.5dB loss and removing the isolator (See Fig. 1) as well as the switch preceding the remotely pumped preamplifier, error free transmission ($BER < 10^{12}$) over a distance of 529.1km is realised as shown by the solid diamond. The total fibre loss experienced by the signal is then 93.8dB.

In conclusion, we have demonstrated error-free transmission at 2.488Gbit/s in an unrepeatered transmission system with a fibre span of 529.1km and a transmission fibre loss of 93.8dB by employing a new SBS suppression technique, high power Raman pump lasers, dispersion compensation, and forward error correction. Excluding the forward error correction coding, a transmission distance of 501.3km is achieved with a fibre loss of 89.7dB.

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Control of soliton-soliton and soliton-dispersive wave interactions in high bit-rate communication systems

R.-J. Essiambre and G.P. Agrawal

Indexing terms: Soliton transmission, Simulation

The authors present numerical simulations of the 80Gbit/s soliton transmission experiment (*Electron. Lett.*, 1994, **30**, pp. 1777-1778) operating in a regime beyond the average-soliton limit and show that dispersive waves and soliton interaction limit the total transmission distance to ~500km, in agreement with the experimental results. Two ways of improving the system performance are presented and discussed. The use of fast saturable absorbers can eliminate interaction between solitons and dispersive waves and increase the transmission distance above 1000km. The soliton-soliton interaction can be made virtually ineffective by using synchronous modulation. Such a lightwave system can transmit a high bit-rate (50–100Gbit/s) soliton signal over transoceanic distances while keeping amplifier spacings larger than the soliton period.

High bit-rate, soliton-based lightwave systems are attracting considerable interest as they are expected to significantly increase the capacity of fibre-optic communication links. However, until recently [1], stable transmission of solitons was achieved in the so-called average-soliton [2] (or guiding-centre-soliton [3]) regime characterised by the amplifier spacing being much smaller than the soliton period. In this regime, the maximum single-channel bit-rate achievable is ~10–15 Gbit/s [4, 5]. Higher bit rates with practical amplifier spacings require the use of shorter solitons having a soliton period shorter than the amplifier spacing. In such a case, the concept of average solitons is not valid for describing soliton propagation. We refer to this new regime of propagation as 'quasi-adiabatic' [6].

We present here the results of numerical simulations for the 80 Gbit/s experiment of Nakazawa *et al.* [1] for which the amplifier spacing was larger (by 60%) than the soliton period. The results show that the system performance is affected not only by soliton-soliton interaction but also by the interaction between solitons and dispersive waves. We show that the system performance can be improved considerably if a saturable absorber is inserted after each in-line amplifier [6], simply because it can remove low-power dispersive waves. We also analyse how system performance can be improved through synchronous modulation.

The propagation of a soliton train in the fibre is governed by a generalised nonlinear Schrödinger equation

$$\frac{\partial u}{\partial z} = -\frac{i}{2}\beta_2\frac{\partial^2 u}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 u}{\partial t^3} - \frac{\alpha}{2}u + i|u|^2 u - T_R u\frac{\partial |u|^2}{\partial t} \quad (1)$$

where a standard notation has been used [7]. The parameters of the simulation are taken from [1]: α = 0.21dB/km and β_2 = –0.25ps^2/km. The 80Gbit/s soliton train is made of fundamental solitons separated by 12.5ps, with widths ranging from 2.7 to 3.0ps (alternating-amplitude solitons [8]), and with random phases. The amplifier spacing of 25km is larger than the 16km soliton period. Each amplifier is followed by an optical filter of 3nm bandwidth, three times broader than the soliton spectrum. The loss for one span is 6dB (5.3dB for the fibre and 0.7dB for connectors) at the central frequency of the filters. The amplifier gain is set to 6.8dB to compensate for the filter-induced excess loss of 0.8dB. To make the simulations as realistic as possible, we include both the third-order dispersion (β_3 = 0.1ps^3/km) and the Raman term (T_R = 6fs), which is responsible for the soliton self-frequency shift.

Numerical simulations performed with a pseudorandom bit pattern of solitons show that the system performance is mainly limited by the bit combinations in which several 1 bits occur together. For this reason, we use an input bit pattern consisting of eight consecutive 1 bits. Fig. 1*a* shows a contour plot of the soliton propagation over 950km. Clearly, the soliton train starts to degrade after 500km, in agreement with the experimental results of [1]. *Two phenomena are responsible for such degradation:* interaction between dispersive waves and the soliton train, and soliton-soliton interaction. Interestingly, no significant differences were observed between the transmission of a soliton train with different amplitudes and a train of identical solitons. The strong action of the filter combined with the Raman effect are believed to be responsible for this unusual behaviour.

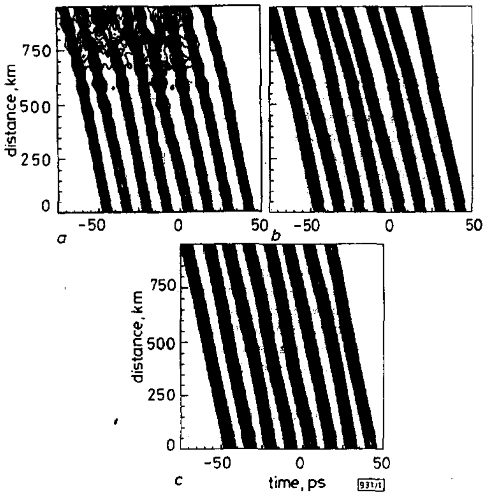

Fig. 1 *Propagation of 80Gbit/s soliton train over 950km for three different schemes*

a Experimental conditions of [1]
b Fast saturable absorber inserted after each amplifier
c Synchronous modulator replacing fast saturable absorber
Tilting of soliton trajectories because of filter-induced and Raman-induced time delays.

How can the performance of the 80-Gbit/s experiment of [1] be improved? Clearly, the solitons are strongly perturbed during propagation since the conditions for the average-soliton regime are not satisfied. A strong perturbation of solitons creates dispersive waves which accumulate over multiple amplifiers and eventually destroy solitons altogether. To limit the growth of the dispersive waves we insert a fast saturable absorber at every amplification stage [6]. Its absorbance is 84% at low power levels and 5% at high power levels. The saturation power of the absorber is taken to be 5% of the soliton input peak power. Fig. 1*b* shows how the saturable absorber can stabilise the soliton train, allowing transmission of solitons over more than 1000km under the operating conditions of [1]. However, even though a fast saturable absorber helps to reduce the interaction between solitons and dispersive waves, soliton-soliton interaction is still a limiting factor. This is apparent in Fig. 1*b* where neighbouring solitons are attracted or repelled depending on their relative phases.

It has been shown [4] that synchronous modulation can be used to eliminate the timing jitter of a soliton train in the average-soliton regime. Can synchronous modulation also eliminate the timing jitter even when the solitons are strongly perturbed (no average soliton)? To answer this question, Fig. 1*c* shows the *results of a simulation under the same conditions as Fig. 1a,* but with a synchronous modulator, having an intensity modulation depth of 30%, inserted after each filter. Our results demonstrate for the first time that the synchronous modulation technique works even under operating conditions beyond the average-soliton regime. Moreover, the use of a modulator with sufficient modulation depth can also limit the growth of dispersive waves without requiring a fast-saturable absorber. Propagation over 10000km at 80Gbit/s with practically no soliton-interaction-induced timing jitter has been observed with this configuration. Amplifier noise should be included for transmission over such long distances. However, it does not affect the system performance significantly in the case of synchronous modulation [4]. If the system is designed with a saturable absorber (to avoid the use of active modulators),it may become necessary to use sliding-frequency guiding filters to avoid the amplifier-noise-induced timing jitter.

In conclusion, our numerical simulations for a high bit-rate (80Gbit/s) soliton communication system, operating in a regime well beyond the average soliton (amplifier spacing larger than the soliton period), show that the limiting factors are the growth of dispersive waves which interact with the soliton train, and the interaction among the solitons themselves. We show that the *transmission distance can be increased considerably by either* inserting fast saturable absorbers (passive control) or using synchronous modulators (active control). Saturable absorbers responding on femtosecond time scales are not easy to obtain but a multiquantum well device [9] or a nonlinear-interferometer-based device (such as a nonlinear fibre-loop mirror [10]) may serve this purpose.

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Demonstration of error free optical soliton transmission over 30000km at 10Gbit/s with signal frequency sliding technique

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Indexing terms: Soliton transmission, Optical communications

10Gbit/s optical soliton transmission in a recirculating loop is demonstrated. The signal frequency sliding technique is employed to reduce the accumulation of ASE noise and timing jitter. Error free ($BER < 10^{-9}$) soliton transmission over 30000km is achieved.

Soliton control techniques in the time domain [1, 2] and frequency domain [3] are promising for ultrahigh speed and ultralong distance transmission because they reduce the timing jitter and saturate the accumulation of amplified spontaneous emission (ASE) noise. A novel sliding frequency technique, the so-called 'signal-frequency sliding in frequency domain' control technique, was recently proposed [4] and demonstrated [5]. This technique involves periodically sliding the ASE noise with a frequency shifter, thus saturating the ASE noise accumulation, while solitons are guided with fixed frequency guiding filters. This leads to a constant soliton frequency along the transmission line, and gives the advantage of soliton propagation without any change in the average fibre dispersion along the line. This avoids the higher-order dispersion effect; a significant advantage over sliding frequency filtering [3]. By using this technique and selecting the appropriate parameters such as the pulse width, peak curvature of the optical filter, frequency shift and average fibre dispersion, we successfully demonstrated the longest error free ($BER < 10^{-9}$) recirculating transmission over 30000km at 10Gbit/s, reported to date.

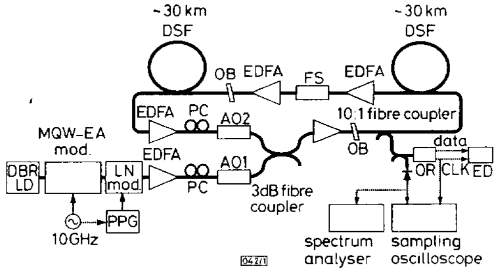

Fig. 1 *Experimental setup*

Fig. 1 shows the experimental setup. A DBR-LD with CW operation and an MQW-EA modulator sinusoidally driven at 10 GHz were employed as the pulse source. The optical pulse trains were modulated by a Ti:LiNbO$_3$ intensity modulator (LN modulator) driven by a pulse pattern generator (PPG) with pseudorandom bit sequences (PRBS 2^7–1). The modulated pulses were amplified in an EDFA and launched into the recirculating loop through an acousto-optic switch (AO1). The recirculating loop consisted of two spans of ~30km dispersion shifted singlemode fibre (DSFs) and four EDFAs pumped with 0.98μm LDs. The loss and zero dispersion wavelength of the DSFs were 0.26dB/km and 1550nm, respectively. The average input power into each fibre was ~–3dBm. The measured population inversion factor n_{sp} for each of the four EDFAs was ~1.2. Two optical bandpass filters (OBs) with a 1nm bandwidth (the average peak curvature = 1.32×10^{-22} (s^2)) were included in the loop to guide the soliton frequency. An acousto-optic frequency shifter (FS) was inserted between the two DSFs to reduce and saturate the ASE noise accumulation. An acousto-optic switch (AO2) and a 3dB fibre coupler closed the loop. The AO2 had two functions: as the loop switch and as the additional frequency shifter. The recirculating pulses were extracted through a 10:1 fibre coupler, and introduced into an optical receiver (OR), having an effective window time of ~32 ps, and a *pin* photodetector (35GHz bandwidth). An RF spectrum analyser and sampling oscilloscope following the *pin* photodetector were used to observe the 10GHz modulation frequency components and the eye patterns, respectively. An error detector (ED) measured the BERs. The initial pulse width, frequency shifts of the FS an AO2, and average fibre dispersion were set at 15ps, 510MHz, 55MHz and 0.27ps/km/nm, respectively. These values were theoretically selected to saturate the BER given by the ASE noise accumulation to $< 10^{-12}$. A more analytic discussion of these results will be presented in [6]. With these parameters, the theoretical transmission distance ($BER = 10^{-12}$) restricted by the timing jitter due to the Gordon-Haus effect and the carrier linewidth of the pulse source (~1MHz) [7], can be estimated to be 40000km. When the timing jitter due to the acoustic effect [3] is considered, the estimated distance decreases to ~28000km.

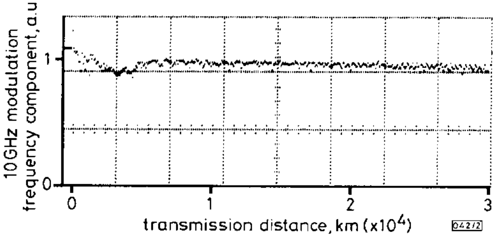

Fig. 2 *10GHz modulation frequency component against transmission distance*

Fig. 2 shows the 10GHz modulation frequency component measured with the RF spectrum analyser against transmission distance. The RF component is almost constant over the 30000km transmission, thus indicating the effective suppression of timing jitter accumulation. Fig. 3*a* and *b* depicts the eye patterns measured with the sampling oscilloscope at 0 and 30000 km, respectively. The eye opening is still clear even after the 30000 km transmission.

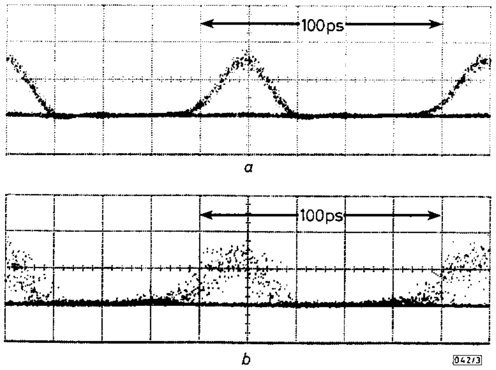

Fig. 3 *Eye patterns*
a 0km
b 30000km

The resultant plot of the BER against transmission distance is shown in Fig. 4. The theoretical timing jitter due to the Gordon-Haus effect and the carrier linewidth of the pulse source is also shown in Fig. 4. The signal frequency sliding technique achieves error free ($BER < 10^{-9}$) soliton transmission over 30000km; SNR and timing jitter do not limit the transmission distance. The