EDFAs have a small signal gain of 25dB and a saturation power of +11dBm.
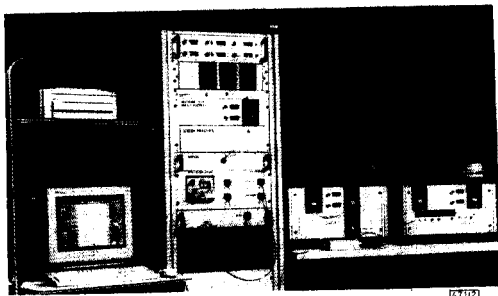

Fig. 2 *Fully connected demonstrator*

The TCDR is composed of a tunable Fabry-Perot filter (FWHM bandwidth of 1Å) [5] and a *pin*-FET receiver with a sensitivity of −32dBm at 155Mbit/s. Fabry-Perot filters are locked to the incoming signal with an optoelectronic closed loop used to track the selected wavelength. The two added wavelengths (λ_s, λ_n) are received separately at the receiving part of the central station. FSK format at 155Mbit/s is used. In this case, the optical filter is also used as an FSK to ASK convertor. Between the central station and the first station, two 2:1 optical switches and a second fibre act as a protection system. A centralised computer-based monitoring system controls the TCDRs and the switches. A panel is used to monitor the configuration of each node in the ring. The reconfiguration of the ring network is achieved by tuning the TCDR with the computer. Various alarms are used to ensure that the automatic network can be restored in the case of a cable being cut or if the traffic changes. A fully connected testbed demonstrator is shown in Fig. 2.
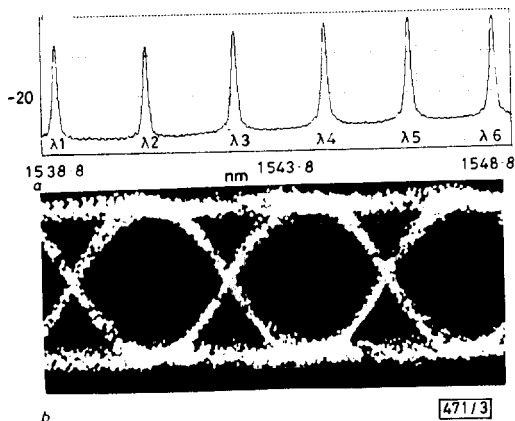

Fig. 3 *Optical spectum at output of second station and demodulated error-free eye diagram at 155Mbit/s*

a Spectrum
b Eye diagram

Results and discussion: Fig. 3 shows the optical spectrum at the output of the second station (after three EDFAs). At the first and the second node, the added wavelengths λ_s and λ_6 are attenuated before being injected into the amplifiers in order to have the same level for all the channels. This enables the SNR differential between the six channels to be reduced after passing through a cascade of EDFAs.

The maximum link losses between nodes were measured using variable optical attenuators at 155Mbit/s. Starting from the central station and coming back to it, link losses are, respectively, 22, 21 and 19dB. FSK transmission was also achieved at λ_2 through 213km of SMF between a transmitter and a receiver of the central station. Fig. 4 shows the demodulated error-free eye diagram at 155Mbit/s.

In the event of fibre failure, optical switches automatically route the information on the protection fibre (self-healing function) and an alarm signal is sent to the control panel. Finally, this WDM ring network is transparent to the bit rate and offers dynamic rearrangeability.

Conclusion: The description and the principles of operation for an experimental WDM ring testbed demonstrator has been presented. The 213km ring network incorporate three reconfigurable WDM nodes with TCDR. Using three EDFAs 62dB link losses can be obtained. A computer incorporated in the testbed controls the node reconfiguration as well as the survivability of the ring. Such a configuration is suitable for the regional layer and allows flexible network evolution.

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Effect of Brillouin scattering on optical fibre communication using solitons

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Indexing terms: Soliton transmission, Brillouin scattering

The limitation imposed by the Brillouin effect on both bright and dark solitons is examined. Bit rates in excess of 100Gbit/s are allowed, although WDM or sliding filters must be used with bright solitons.

Introduction: Bright soliton communication systems appear poised to become a reality. Recent experimental work has demonstrated 15Gbit/s over 25000km [1], the latest achievement in a long series of breakthroughs. By contrast, despite the continued interest in dark solitons [2], the only experiments to date have created dark solitons on top of a pulse of finite duration [3, 4]. The difficulties in generating dark solitons as well as the large power requirements are to blame. Reasons given in the literature for interest in dark soliton communications include reduced susceptibility to noise, reduced mutual interactions and, assuming that the spontaneous emission coefficient remains the same, a slightly reduced Gordon-Haus jitter relative to bright solitons [5, 6]. It is not surprising that dark solitons are less susceptible to noise given their substantially higher power requirements per bit. For example, if we assume that solitons with an FWHM duration of 16ps are used and that the bit spacing is 100ps, numbers consistent with recent experiments [1], then dark soliton transmission requires 10 times the average power of bright soliton transmission.

The higher power requirements of dark solitons leads to the supposition that they are more susceptible to power dependent effects than are bright solitons. Such effects include electrostriction which has proved quite troubling for bright soliton transmission [7, 8]. Here, we determine the bit rate limitations imposed on both

bright and dark soliton transmission by Brillouin scattering and find that the limitation imposed on single wavelength bright soliton transmission is actually more severe than the limitation imposed on dark soliton transmission. The reason, as we shall show, is that soliton transmission signals have nearly coherent components whose bandwidth equals the bandwidth of the laser source and fits within the Brillouin bandwidth, whereas dark soliton transmission signals are incoherent.

Bright solitons: The growth rate Γ of the Brillouin instability is given by $\Gamma = gI_p$, where $g = 5 \times 10^{-11}$m/W is the Brillouin gain coefficient and I_p is the pump intensity, for nearly coherent contributions whose spectral width is less than the Brillouin linewidth $\Delta\nu_B = 17$MHz [9, 10]. The growth rate is given by $\Gamma = \pi g S_p(\nu)\Delta\nu_B$, where $S_p(\nu)$ is the pump spectral intensity, for incoherent contributions whose spectral width is greater than $\Delta\nu_B$. To calculate the spectral intensity, we first note that the autocorrelation function $C(t)$ for a bright soliton train is governed by the periodicity relation

$$C(nT + t') = p_{11}(nT)C(t') \qquad (1)$$

where T is the bit period of the soliton train, n is any integer, $-T/2 < t' < T/2$, and $p_{11}(nT)$ is the probability of obtaining two 1s in the same time slot when the soliton stream is offset by nT. Assuming an equal probability, uncorrelated stream of 1s and 0s, we find that $p_{11}(nT) = 0.25(1 + \delta_{n,0})$ Using the usual functional form for bright solitons [9, 10] and taking the Fourier transform of eqn. 1, we obtain

$$S_p(\nu) = 0.322\pi^2 \frac{\tau^2}{4T} I_{sol} \text{sech}^2(0.567\pi^2\tau\nu)$$
$$\times \left[1 + \frac{1}{T} \sum_{n=-\infty}^{\infty} \delta(\nu - n/T)\right] \qquad (2)$$

where τ is the FWHM duration of the soliton pulse. The quantity $I_{sol} = 0.777[\lambda^3/\pi^2][D/cn_2\tau^2]$ is the peak intensity of the soliton averaged over the effective area of the fibre core, where $\lambda = 1.55\mu$m is the wavelength of light, D is the dispersion, c is the speed of light and $n_2 = 3.2 \times 10^{-16}$cm^2/W is the Kerr coefficient. The first term in the square bracket of eqn. 2 is the incoherent contribution to the spectral intensity and the second term is the nearly coherent contribution. The maximum growth rate Γ_{bright} which occurs at $\nu = 0$ is given by

$$\Gamma_{bright} = 0.322\frac{\pi^2}{4}gI_{sol}\frac{\tau^2}{T^2}(\pi\Delta\nu_B T + 1) \qquad (3)$$

The first term is negligible. For example, if we consider a 10Gbit/s soliton stream, we find that $\pi\Delta\nu_B T = 5.3 \times 10^{-3}$.

Traditionally, one determines the length scale L over which the Brillouin effect has a significant impact is determined by setting $(\Gamma - \Gamma_0)L = 21$ [10] where Γ_0 is the material loss. At this length the pump and Stokes waves have roughly equal amplitudes. In a long-distance communication system the backward propagating waves due to the Brillouin instability can be filtered out by isolators at the amplifiers. In addition, we must have negligible power in the Stokes wave to avoid information degradation. We therefore use the conservative criterion $(\Gamma - \Gamma_0)L_{amp} < 10$, where L_{amp} is the amplifier spacing, to estimate the range of safe values. We then find that

$$\left[\frac{\lambda^3}{16}\frac{D}{cn_2T^2}g - \Gamma_0\right]L_{amp} < 10 \qquad (4)$$

where $\Gamma_0 = 4.6 \times 10^{-2}$km^{-1} is the fibre loss corresponding to 0.2dB/km. Assuming that $L_{amp} = 30$km and noting that $T = 1/f_{bit}$, where f_{bit} is the frequency, we obtain

$$D^{1/2}[\text{ps/nm·km}]f_{bit}[\text{GHz}] < 18 \qquad (5)$$

and, in particular, if $D = 0.5$ps/nm·km, then $f_{bit} < 25$GHz.

We emphasise that this limit applies to a single wavelength stream of solitons. The Brillouin effect imposes no limit on WDM so that limits in excess of 100Gbits/s can be obtained by using more than four channels. Moreover, sliding filters can eliminate the Brillouin effect.

Dark solitons: To calculate Γ, we first note that $C(t) = 0$ if $|t| > T$ so that the signal is incoherent and the pump spectrum is strictly broadband. Because $S_p(\nu)$ has its maximum at $\nu = 0$, it suffices to calculate $S_p(0)$. The probability that a dark soliton is present in a bit period when the signal is a random string of 1s and 0s is 1/2. Thus, we obtain

$$S_p(0) = \frac{1}{2}I_{sol}\int_{-T/2}^{T/2}[1 + \tanh^2(1.76t/\tau)]dt$$
$$= I_{sol}(2T - 1.135\tau) \qquad (6)$$

where the first term in the integral is the contribution when the dark soliton is absent and the second term is the contribution when it is present, so that

$$\Gamma_{dark} = \pi g\Delta\nu_B I_{sol}(2T - 1.135\tau) \qquad (7)$$

We then find that $\Gamma_{dark}/\Gamma_{bright} \approx 7.91(\Delta\nu_B T)(T/\tau)^2$. Assuming $T = 100$ps and $\tau = 16$ps, which are consistent with recent experiments, we obtain $\Gamma_{dark}/\Gamma_{bright} \approx 0.53$ so that the growth rates of dark and bright solitons are comparable. The effect of the added power of the dark solitons is compensated by their greater incoherence.

Using the same criterion which we previously applied to bright solitons, we find

$$\left[0.495\frac{\lambda^3 DT}{cn_2\tau^2}g\Delta\nu_B(1 - 0.567\tau/T) - \Gamma_0\right]L_{amp} < 10 \qquad (8)$$

is required to avoid the Brillouin instability. Setting $\tau/T = 6.25$ and using as before $L_{amp} = 30$km, we obtain

$$D[\text{ps/nm·km}]f_{bit}[\text{GHz}] < 65 \qquad (9)$$

If we set $D = 0.5$ps/nm·km, we find that bit rates are limited to being less than 130Gbits/s.

An important practical caveat is that one must guard against coherent bursts of bits of length $(\pi\Delta\nu_B T)^{-1}$ or greater; otherwise, the attainable bit rate is seriously degraded.

Conclusion: We have determined the limitations which the Brillouin instability imposes on soliton transmission systems. Assuming that backwards propagating waves are filtered out every 30km and dispersion shifted fibre with $D = 0.5$ps/nm·km is used, we find that single wavelength bright soliton transmission is limited to a maximum of 25GHz and dark soliton transmission is limited to a maximum of 130GHz. The limitation on bright soliton transmission can be increased many-fold by the use of WDM and can be eliminated by the use of sliding filters.

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Experimental demonstration of 100 GHz dark soliton generation and propagation using a dispersion decreasing fibre

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Indexing terms: Soliton transmission, Nonlinear optics, Optical dispersion

The authors report the first experimental demonstration of high-frequency dark soliton generation through nonlinear conversion of a high-intensity beat signal in a + GVD dispersion decreasing fibre. High quality, 1.6ps dark soliton generation at 100GHz is obtained. The quality of the pulses and the stability of the trains are demonstrated by propagation through a 2.2km span of + GVD dispersion shifted fibre (≈ two soliton periods).

The generation and propagation of bright and dark soliton pulses is an area of great scientific interest with relevance to many future telecommunication and optical-processing applications. Bright solitons have been the subject of intense experimental investigation. However, the experimental study of dark soliton behaviour has been limited. This situation is in no small part due to the difficulty of generating such pulse forms [1–4].

In this Letter we describe an extremely simple, all-fibre source of 100GHz, 1.6ps dark solitons. Unlike previous schemes for dark soliton generation the pulses are formed on a true CW background rather than on a slowly broadening short pulse [2, 3, 4]. In addition, we demonstrate the stable propagation of such trains over a distance of 2.2km (≈ two soliton periods).

The technique is based on the principle of nonlinear conversion of a high-frequency beat signal into a soliton train through nonlinear propagation in a fibre of slowly decreasing dispersion [5]. The technique has been applied successfully to the generation of high-frequency, bright CW soliton trains using a fibre of steadily decreasing anomalous dispersion (−GVD) [6]. However, as pointed out by a number of authors, it can in principle also be extended to the case of dark soliton generation if a fibre with slowly varying normal dispersion (+GVD) is used [5, 7]. The results presented here constitute the first experimental demonstration of the technique. Note that dark pulse formation from a beat signal by propagation in a fibre with uniform, low, +GVD has already been demonstrated [8, 9]. However, in this instance, the trains are not stable but evolve and decay periodically with propagation [8, 9].

The experimental configuration is illustrated in Fig. 1. Two single-frequency DFB lasers operating around 1548 nm were combined using a 50:50 coupler. The resulting beat signal (temperature tuned to 100GHz) was then passed through a two stage 1064nm pumped Er³⁺/Yb³⁺-doped fibre amplifier incorporating a 1nm optical bandpass filter. Up to 400mW of average signal power was available at the amplifier output. To reduce gain saturation effects within the amplifer and increase the signal power to a level suitable for dark soliton formation, the diodes could be synchronously square-wave modulated. Mark space ratios (MSRs) as high as 10:1 could be used at little expense in average signal output power. A diode pulse duration of 50ns was used. Note that for 100GHz

pulse generation each 50ns diode pulse contains ~5000 pulses. Peak powers as high as 4W were therefore available at the +GVD dispersion decreasing fibre (+DDF) input. Furthermore, the diode modulation also eliminated the problem of Brillouin scattering which is frequently encountered when propagating high-intensity narrow-linewidth CW beams in long lengths of low loss optical fibre [6].
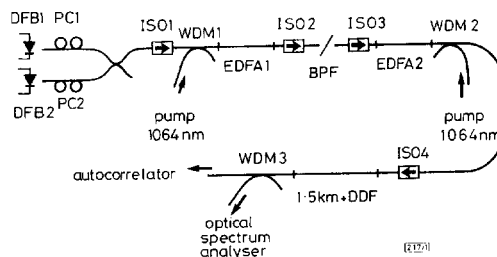

Fig. 1 *Experimental configuration of dark soliton source*

The +GVD dispersion decreasing fibre (+DDF) had a length of 1.5km and was fabricated at Southampton University using similar technology to that used for conventional −GVD DDF fabrication [10]. The dispersion followed a hyperbolic profile along the fibre length, ranging from −8ps/(nm.km) at the input to −1ps/(nm.km) at the output. This corresponded to a diameter taper along the length from 75µm at the input to 93µm. The ratio of fibre core diameter to fibre outer diameter was 0.048. The total fibre loss was 2.1dB. For convenience, a WDM coupler was spliced to the +DDF output to enable the pulse trains to be simultaneously monitored in both the temporal domain (with an autocorrelator) and in the spectral domain.
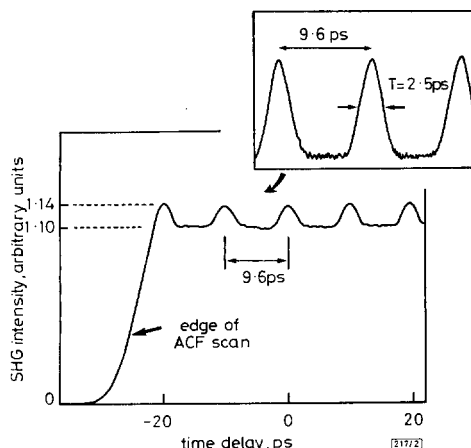

Fig. 2 *Autocorrelation trace of 103GHz, 1.6ps dark soliton train at source output*

Pulse train formation was examined for a wide range of input beat-signal powers and repetition frequencies. Optimum performance was found at a repetition rate of ~100GHz for an input beat-signal power of ~1.2W (diodes driven at $MSR = 4:1$). A typical background-free autocorrelation function (ACF) trace of the dark pulse train obtained at the +DDF output is shown in Fig. 2 and the corresponding optical spectrum in Fig. 3. The input beat signal power was 1.17W and the beat frequency was 103GHz. The ACF exhibits small peaks on a large background, as expected for a dark pulse train. The period of the peaks, 9.6ps, agrees well with the spectral periodicity (0.82nm = 103GHz) observed in Fig. 3. A close up of the ACF indicates that the dark pulses are well separated and have a good sech² form. The pulse duration, as measured from the ACF peaks, is estimated at 1.6(±0.1)ps, corresponding to an MSR of 6.0(±0.4):1. The ACF shoulder between adjacent pulses is also extremely flat indicating that a high-quality dark pulse train has indeed formed. The peak to