60, we can obtain a capacity equal to 40006 and 84059, respectively. Therefore, the PBHC provides an extremely high storage capacity for pattern pairs. The practical capacity of the PBHC in the worst case is estimated, thereby allowing us to predetermine the size of the PBHC.

Acknowledgments: This research was partially supported by National Science Council under grant NSC 89-2219-E-110-001, 89-2215-E-110-014 and 89-2215-E-110-017.

5 August 1999
Electronics Letters Online No: 19991344
DOI: 10.1049/el:19991344

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320Gbit/s (8 × 40 Gbit/s) WDM transmission over 367km with 120km repeater spacing using carrier-suppressed return-to-zero format

Y. Miyamoto, A. Hirano, K. Yonenaga, A. Sano, H. Toba, K. Murata and O. Mitomi

The authors demonstrate +11dBm-per-channel 320Gbit/s (8 × 40Gbit/s) WDM transmission over a 367km zero-dispersion-flattened transmission line with 120km repeater spacing using a nonlinearity-tolerant carrier-suppressed return-to-zero format.

Introduction: When targetting WDM systems with total capacities in excess of terabits per second, there are several advantages in increasing the electrical-time-division-multiplexed (ETDM) channel rate to 40Gbit/s [1]. It is possible to reduce the number of multiplexed channels to less than 25, which simplifies network management and saves on wavelength resources. The channel power of such WDM systems should be linearly increased as the line rate increases in order to return the same signal-to-noise ratio. A numerical simulation has shown that the return-to-zero (RZ) format offers a large power margin in dispersion-managed transmission lines using singlemode fibre (SMF) at a line rate of 40Gbit/s [2], and there are several experimental reports of using a dispersion-managed line [3 – 5]. No experimental report has, however, detailed 40Gbit/s RZ channel WDM transmission performance at repeater-output powers > +10dBm/channel, levels at which several fibre nonlinear effects, such as self-phase modulation (SPM) and cross-phase modulation (XPM), become significant in determining the system performance.

In this Letter, we show that our proposed optical-carrier-suppressed RZ (CS-RZ) format has a larger power margin than the conventional RZ signal format in an SMF-based, dispersion-managed transmission line (zero-dispersion-flattened (ZDF) transmission line [4]). We demonstrate 320Gbit/s (8 × 40Gbit/s) WDM transmission with 120km repeater spacing for the first time over a 367km ZDF transmission line. This is possible because the CS-RZ format achieves record 40Gbit/s channel power of +11dBm (total power: +20dBm/8-channel).

Experimental setup: The experimental setup is shown in Fig. 1. In the transmitter, the eight optical carriers were simultaneously modulated with the 40Gbit/s non-return-to-zero (NRZ) format ($2^7 - 1$ pseudorandom binary sequence) using an InP-HEMT multiplexer IC [6] and a push-pull type $LiNbO_3$ Mach-Zehnder (LN-MZ) modulator (MZ 1) [7]. The signal wavelengths ranged from 1546.1nm (channel 1) to 1557.3nm (channel 8) with 200GHz spacing. The 40Gbit/s NRZ optical signals were boosted and converted into 40Gbit/s CS-RZ signals in a newly proposed MZ-modulator pulse generator. In the optical pulse generator, the LN-MZ modulator (MZ 2) [7] was biased at the transmission null.

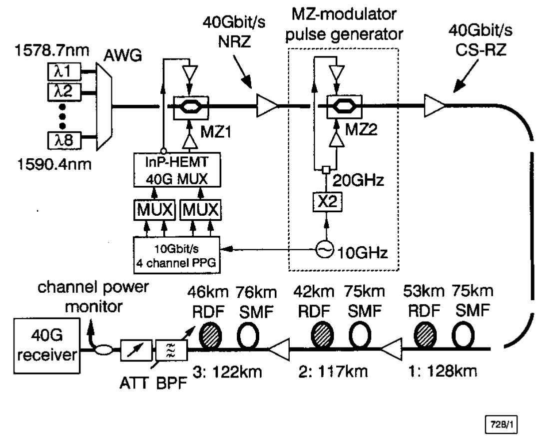

Fig. 1 *Experimental setup*

Two pairs of 20GHz clock signals were fed to each electrode of the modulator (MZ 2). The phase-encoding characteristics of the modulator yielded a 40GHz chirpless CS-RZ signal from a 20GHz electrical input. The full width at half maximum (FWHM) measured by a streak camera was 12ps. To generate a conventional RZ signal with an FWHM of 12ps, the output of the MZ 2 modulator (driven by 40GHz signals) was used with the normal bias condition: the mid-point between the transmission null and peak. The carrier component of the CS-RZ signal spectrum was suppressed and the spectral bandwidth of the CS-RZ signal was smaller than that of the conventional RZ signal, as shown in Fig. 2. In the receiver, the 320Gbit/s signal was WDM-demultiplexed using a tunable bandpass filter with 0.9nm bandwidth, and was optically demultiplexed into 20Gbit/s signals to check the bit error rate (BER) [5]. The 367km ZDF transmission line consisted of three repeater spans joined by two EDFA in-line repeaters. Each span consisted of SMF and reverse-dispersion fibre (RDF) [8]. The losses of the three sections were 29.06dB (1: 0.23dB/km), 28.04dB (2: 0.24dB/km) and 26.52dB (3: 0.22dB/km). The total dispersion of the 367km ZDF line ranged from –3ps/nm to +16ps/nm over the 8-channel signal wavelengths, and a dispersion-flattened characteristic was obtained for a 10nm wavelength range.

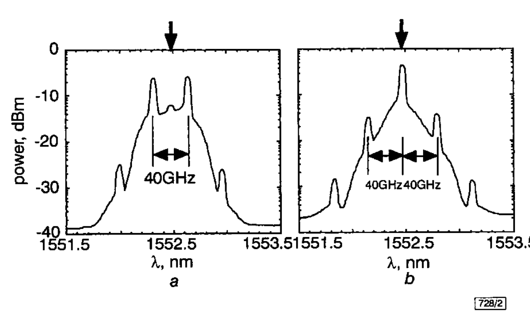

Fig. 2 *40Gbit/s modulation spectra (↓: optical carrier frequency)*
a Proposed CS-RZ format
b Conventional RZ format

40Gbit/s CS-RZ single-channel transmission: The CS-RZ and conventional RZ formats were compared in terms of single-channel transmission performance, both numerically simulated and measured, in the 367km ZDF line. In the numerical simulations, the CS-RZ format enhanced the maximum repeater power (defined as the eye-opening penalty of 1dB) by 1.3dB compared to the conventional RZ format, as shown in Fig. 3*a*. Fig. 3*b* shows the experimental results. The repeater-output-power enhancement offered by the CS-RZ format was 1.4dB and was in good agreement with the numerical simulation. The power penalty at repeater output powers < +8dBm was due to the SNR degradation. The NRZ transmission failed to achieve error-free operation for repeater powers from 4–10dBm due to both SNR degradation and nonlinear degradation.

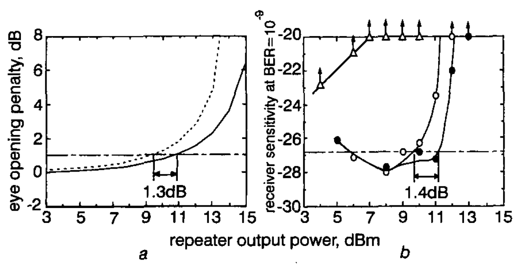

Fig. 3 *40Gbit/s single-channel transmission experiment over 367km ZDF transmission line*

a Simulation results
——— CS-RZ
·········· conventional RZ
b Experimental results
● CS-RZ
○ conventional RZ
△ NRZ
↑ error floor of > BER = 10^{-9}

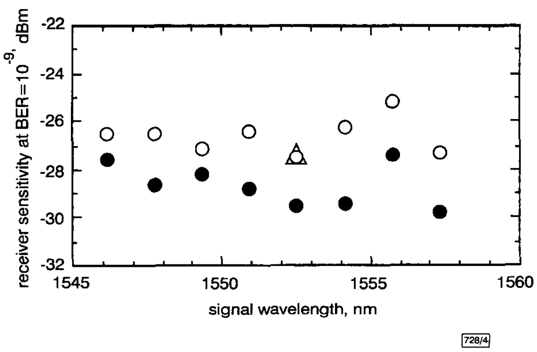

Fig. 4 *320Gbit/s (8 × 40 Gbit/s) WDM transmission experiment using 40Gbit/s CS-RZ signals with channel power of +11dBm*

● WDM 0km
○ WDM after 367km
△ single-channel after 367km

320Gbit/s (8 × 40 Gbit/s) CS-RZ WDM transmission: We conducted 8-channel CS-RZ WDM transmission over a 367km ZDF line with total repeater output power of +20dBm (+11dBm/channel). Fig. 4 shows the channel variation in receiver sensitivity at a BER of 10^{-9} with 40Gbit/s transmission. All 40Gbit/s channels were successfully transmitted over the 367km ZDF transmission line. The receiver sensitivity of channel 5 (–27.4dBm) obtained in single-channel transmission was the same as that achieved in WDM transmission. This result shows that the CS-RZ pulse format keeps SPM tolerance high even in the WDM configuration and that there is no excess penalty caused by the XPM and four-wave mixing induced nonlinear crosstalk.

Conclusion: We have proposed a CS-RZ format that reduces the nonlinear impairments in SMF-based dispersion-managed lines. In tests, it achieved record channel power of +11dBm, a level impossible to achieve using the conventional RZ format. The CS-RZ format yielded, for the first time, 40Gbit/s/channel WDM transmission across a 367km ZDF transmission line based on SMF with 120km in-line repeater spacing and without any terminal dispersion equalisation.

Acknowledgment: The authors would like to thank Ken-ichi Sato for his continuous encouragement and also K. Sato and M. Murakami for fruitful discussions.

6 October 1999
Electronics Letters Online No: 19991373
DOI: 10.1049/el:19991373

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Complete intensity and phase characterisation of optical pulse trains at terahertz repetition rates

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Complete intensity and phase characterisation of optical pulse trains at terahertz repetition rates is carried out using an adapted frequency-resolved optical gating technique. The experimental characterisation of a 2.5THz train of dark solitons in an optical fibre is in good agreement with numerical simulations.

Introduction: The development of sources of optical pulse trains at terahertz (THz) repetition rates has recently attracted much attention because of important applications in generating narrowband THz electromagnetic radiation for millimetre-wave communications and far-infrared spectroscopy [1, 2]. Several schemes for generating THz optical pulse trains have been developed, including beat-frequency generation using dual wavelength lasers [3] and the generation of soliton-like pulse trains in optical fibres [4, 5]. A major difficulty with experiments studying THz optical pulse trains is that the subpicosecond structure of the pulse train cannot be directly measured using photodiodes or streak cameras, and pulse train characterisation is usually performed indirectly using spectral and autocorrelation measurements [3 – 5]. It is well-known, however, that spectral and autocorrelation measurements do not provide complete intensity and phase characterisation and, for sub-picosecond pulses from modelocked lasers, these measurements are now routinely replaced by the complete pulse character-