10-Gb/s Transmission of NRZ over 10 000 km and Solitons over 13 500 km Error-Free in the Same Dispersion-Managed System

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***Abstract*— A dispersion management scheme that is capable of supporting both dispersion-managed solitons and nonreturn-to-zero (NRZ) data formats as well as intermediate formats is demonstrated for error-free long-haul transmission at 10 Gb/s in excess of 9500 km. This experimental tool can be used to directly compare the different data formats. Our results suggest that a format between standard solitons and standard NRZ, such as dispersion-managed solitons or phase-modulated NRZ, may have significant advantages.**

***Index Terms*— Dispersion management, NRZ, solitons, transmission systems.**

CONVENTIONAL wisdom has long held that standard nonreturn-to-zero (NRZ) and pure soliton systems are fundamentally different and require different transmission lines to operate successfully. That is undoubtedly the case for standard solitons in which case the dispersion is fixed. However, we demonstrate that in the case of dispersion-managed solitons a direct comparison is possible by transmitting in the same recirculating loop NRZ signals over 9500 km and dispersion-managed solitons over 13 500 km—both at 10 Gb/s. We note that the transmission distances in both cases are comparable to the best results that have been achieved separately for 10 Gb/s single channel NRZ propagation [1] and dispersion-managed soliton propagation [2], [3].

Dispersion-managed soliton transmission systems consist of periodically alternating spans of anomalous and normal dispersion fiber in which the path-averaged dispersion at the wavelength of the transmission channel is anomalous. The key breakthrough in our system was the recognition that dispersion-managed solitons could be transmitted in optical fiber that is almost entirely in the normal dispersion regime [4]. In this way, the dispersion map is similar to that used in NRZ transmission. The only difference is in the path-averaged dispersion at the wavelength of the transmission channel—normal for NRZ data and anomalous for dispersion-managed soliton data.

We show that our recirculating loop design allows for a careful comparison of various data formats within the control of a single test-bed. Recently, there has been considerable interest in the investigation of pulse formats intermediate to standard solitons and standard NRZ signals. The intermediate formats include phase and/or amplitude modulated NRZ signals, return-to-zero (RZ) signals, and dispersion-managed solitons. The key distinction between RZ signals and dispersion-managed solitons is not the shape, which can be similar in both cases, but rather that dispersion-managed solitons are periodically stationary, returning to the same shape after one period. While in the case of RZ signals, accumulated dispersion and nonlinearity leads to distortion of the pulse shape. In this letter we will demonstrate the wide ranging capabilities of our system design by error free transmission of standard NRZ signals, bit-synchronous phase modulated NRZ signals, and dispersion-managed solitons over distances exceeding 9000 km.

The transmission system is a dispersion-managed recirculating fiber loop approximately 107 km in length. It contains 100 km of dispersion-shifted fiber with a normal dispersion, $D = -1.2$ ps/nm-km at 1550 nm and approximately 7 km of standard fiber with anomalous dispersion, $D = +16.5$ ps/nm·km at 1550 nm. Five erbium-doped fiber amplifiers (EDFA's) are placed inside the loop. An additional acoustooptic frequency shifter in series cancels the optical frequency shift (100 MHz) due to the acoustooptic loop switch. In this way, both the NRZ and soliton systems experience no net frequency shift (frequency sliding) with each loop cycle. There is a single, tunable optical bandpass filter in the loop with $\mathrm{FWHM} \cong 1.2$ nm. The soliton source is a continuous-wave (CW) laser diode followed by a phase modulator driven at the clock frequency. The phase-modulated CW spectrum is then filtered by a fiber grating to produce RZ pulses with a duration ≅20 ps [5], [6]. For NRZ pulse generation we simply removed the fiber-grating filter. The same laser diode is used for both soliton and NRZ pulse generation. Since the input wavelength is nearly the same in both cases, the length of the anomalous dispersion span is adjusted to 7.5 km for soliton transmission and 6.5 km for NRZ transmission to obtain the desired path-averaged dispersion at the wavelength of the transmission channel. Bit-error rate (BER) measurements are made using a PRBS data pattern length equal to $2^{23}-1$. A cycle of our loop contains approximately 5.3 Mb of data and

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is repeated every 100 ms, such that the error-counting duty cycle is fixed for all transmission distances up to 20 000 km. Due to transients arising from the 100-ns switching speed of the acoustooptic modulators, about 80% of the loop data are gated for BER measurements. Therefore, our experiments require 250 s to accumulate 10 Gb of data. Because of this duty cycle, we choose to define the amplitude and phase margins in our experiments to be at a level that has a constant BER $= 1 \times 10^{-6}$.

The first experiment is the transmission of dispersion-managed solitons. Using dispersion-management with solitons offers some significant advantages over the standard approach in which the optical fiber is mostly or entirely in the anomalous dispersion regime, such as improved signal-to-noise ratio and reduced Gordon–Haus jitter originating from enhanced pulse energy [7], [8]. The path-averaged dispersion is +0.15 ps/nm-km (anomalous) at the transmission wavelength of 1551.7 nm. The average power measured in the loop is approximately 2–3 times larger than what is expected in an ideal uniform dispersion soliton transmission system [4], [9]. The received eye patterns at 500 km and 13 500 km are shown in Fig. 1 at (a) 500 km and (b) 13 500 km. A BER approximately equal to 1×10^{-10} was measured at the transmission distance of 13 500 km. The amplitude margin defined by the voltage decision level for constant BER equal to 1×10^{-6} is shown in Fig. 2 as a function of the transmission distance. The upper (lower) curve depicts the amplitude noise in the marks (spaces). This data clearly shows that the accumulated, amplified spontaneous emission (ASE) noise at the space decision level is growing rapidly with distance and ultimately leads to significant errors that limits the maximum error-free transmission distance. The amplitude fluctuations of the soliton pulses are small due to stabilization from the optical bandpass filter.

The standard deviation of the timing jitter is measured through the reduction of the phase margin at the receiver and is found to be ≅3.5 ps at 15 000 km. The timing window of the receiver is 65 ps which would allow for a maximum of a 5.4 ps standard deviation in timing jitter to maintain a BER $= 1 \times 10^{-9}$. We have determined that timing jitter would limit the error-free transmission at a distance of 20 000 km. The timing jitter is almost entirely due to the Gordon–Haus effect and can be predicted by the standard analytical theory taking into account filtering as well as the soliton power enhancement [10].

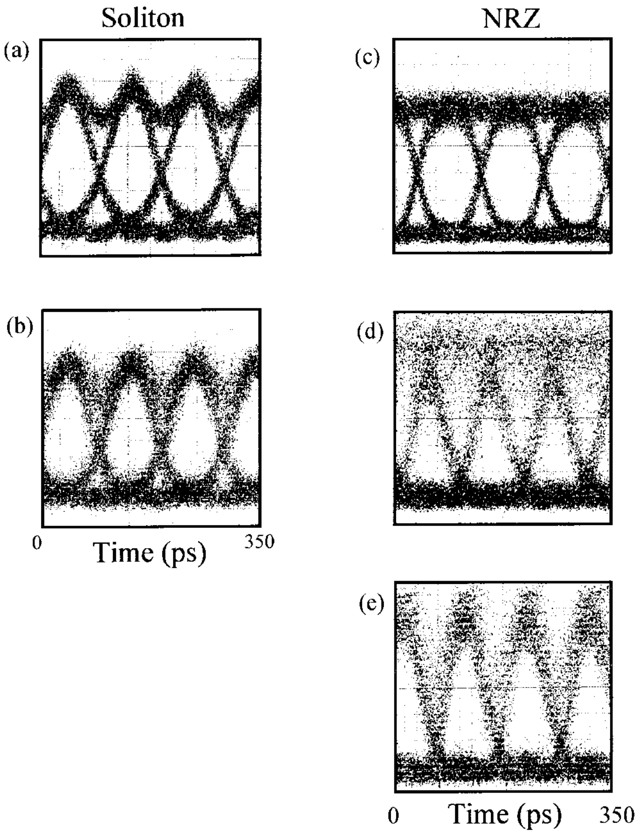

Fig. 1. Received eye patterns for soliton data after (a) 500 km and (b) 13 500 km. Received eye patterns for NRZ data after (c) 500 km, (d) 8500 km, and (e) 8500 km using external phase modulation.

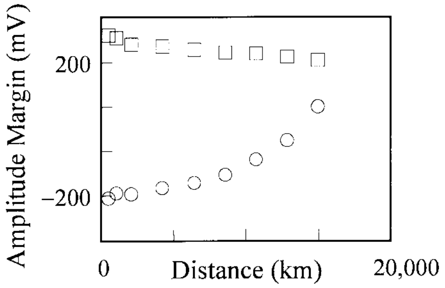

Fig. 2. Amplitude margin defined by the decision level for a constant BER of 1×10^{-6} as a function of distance. The squares (circles) depict the amplitude noise of the marks (spaces) for dispersion managed soliton transmission.

The second set of experiments is NRZ transmission. The path-averaged dispersion is −0.02 ps/nm·km (normal) at the transmission wavelength of 1551.7 nm. The average power (−4 ± 1 dBm) inside the loop is approximately the same as that in the dispersion-managed soliton transmission experiment. We first examined standard NRZ transmission without phase modulation. The received eye patterns are shown in Fig. 1 for (c) 500-km and (d) 8500-km transmission. At a transmission distance of 8500 km, a BER $\leq 5 \times 10^{-9}$ is measured using standard NRZ pulses with no phase or amplitude modulation. It is apparent from the standard NRZ eye pattern in Fig. 1(d) that the isolated marks experience significant pulse compression while sequences of marks do not appreciably compress but experience significant amplitude fluctuations. This is consistent with the observations of a previous NRZ long-haul experiment at 10 Gb/s [1].

We next examined NRZ transmission with bit synchronous phase modulation [11]. The addition of a weak sinusoidal phase modulation yields nearly a factor of 100 improvement in the error performance having a measured BER $\leq 7 \times 10^{-11}$ at the distance of 8500 km. The optical phase modulation depth is approximately 0.2π. The addition of the weak phase modulation separates sequences of marks into independent RZ-like pulses, thus removing the mark rail as seen in Fig. 1(e). An isolated mark obtains a significant chirp caused by the fiber nonlinearity, which enables the pulse to compress in the dispersion-managed fiber system. The addition of the weak

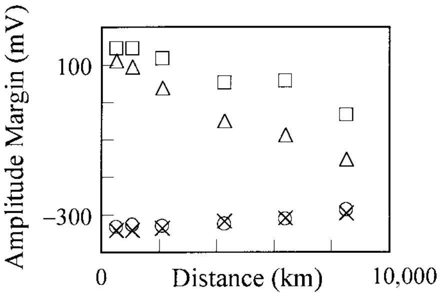

Fig. 3. Amplitude margin defined by the decision level for a constant BER of 1×10^{-6} as a function of distance. The triangles (crosses) depict the amplitude noise of the marks (spaces) for standard NRZ transmission. The squares (circles) depict the amplitude noise of the marks (spaces) for phase-modulated NRZ transmission.

phase modulation provides a necessary pre-chirp such that a sequence of marks will separate and compress.

The amplitude margin defined by the decision level for constant BER of 1×10^{-6} is shown in Fig. 3 as a function of the transmission distance. The upper curves depict the amplitude noise in the markswith (squares) and without (triangles) phase modulation. The lower curves depict the noise accumulation in the spaces with (circles) and without (crosses) phase modulation. The advantage of separating adjacent marks by phase modulation is evident by the large improvement in the amplitude margin. To date, our best error performance is a measured BER $< 1 \times 10^{-9}$ at transmission distances of 9500 km without phase modulation and 10 600 km with phase modulation.

It should be noted that the presence of the optical bandpass filter is necessary in these experiments to eliminate the strong growth of the ASE from the EDFA's. It is observed that the interaction of both pulse formats with this filter is significant. The advantage of the filter for solitons is improved amplitude and jitter performance at the expense of ASE noise accumulation. It is not clear what impact the filter has on the NRZ system. Therefore, the comparison in this work reflects an uncertainty in the optimum conditions for both NRZ and soliton formats. However, our results do show the classical characteristics of noise accumulation leading to eye closure in these systems. For stationary filtered soliton systems, the eye closure is dominated by noise accumulation on the space rails and for NRZ systems the eye closure is dominated by noise accumulation on the mark rails [1], [12].

The principal focus of the work reported here has been to demonstrate a tool that can be used to study a variety of formats between standard NRZ signals and standard solitons. So, we leave a detailed comparison of the formats for the future. However, we think it worthwhile to point out that our work to date suggests that intermediate formats may be more advantageous than either of the two extremes. First, we note that dispersion-managed solitons are not strict solitons in any sense since like NRZ signals they undergo large changes in shape during their evolution and use a dispersion map like NRZ. However, like solitons and unlike NRZ signals, nonlinearity does not lead to accumulated nonlinear distortion since the pulses periodically return to the same shape; in effect they are periodically stationary pulses. Work by others and ourselves show that this format, which is a step toward NRZ transmission from solitons, behaves better than standard solitons without pulse control using sliding filters or retiming [2], [3], [8], [10]. Conversely, we and others [13] have shown that phase- and/or amplitude-modulated NRZ signals, which lead to RZ pulses that resemble solitons far more closely than standard NRZ signals, behave better than standard NRZ. So, what is the optimal format? Is periodic stationarity that avoids accumulated nonlinearity really important in practice? Very recent work by Bergano *et al.* [13], although it included no periodically stationary pulses, suggests that the optimal format may depend on the channel's central wavelength. We believe that the tool presented here will play an important role in investigating these issues.

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