Timing-jitter reduction for a dispersion-managed soliton system: experimental evidence

Gary M. Carter, John M. Jacob, and Curtis R. Menyuk

Department of Computer Science and Electrical Engineering, University of Maryland Baltimore County, Baltimore, Maryland 21250, and the Laboratory for Physical Sciences, 8050 Greenmead Drive, College Park, Maryland 20740

Ekaterina A. Golovchenko and Alexei N. Pilipetskii

Department of Computer Science and Electrical Engineering, University of Maryland Baltimore County, Baltimore, Maryland 21250

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We have measured the timing jitter for dispersion-managed solitons in a recirculating loop for distances up to 20,000 km. The data were obtained with modulated data, $2^7 - 1$ and $2^{23} - 1$ pseudorandom binary sequence patterns, at 10-Gbit/s rates and with an unmodulated pulse train at 10 GHz. We have obtained good agreement with our data, using a filtered Gordon–Haus model for the timing jitter reduced by the energy enhancement of our solitons relative to solitons in a fiber with a constant dispersion equal to our map's path-average dispersion. We have also measured a bit-error rate of $<10^{-9}$ at a distance of 15,000 km. © 1997 Optical Society of America

There has been a great deal of interest in enhanced-power, dispersion-managed solitons.[1] Since their introduction impressive gains have been made in soliton transmission without frequency sliding and in some cases without in-line optical filters.[2] The solitonlike pulse propagating in the dispersion map has its energy enhanced by a factor ξ relative to a pulse propagating in a constant-dispersion fiber with the same path-average dispersion D and pulse width τ.[1] For solitons the pulse energy is proportional to D/τ, and thus amplitude errors rise as D is reduced for a given τ.[3] For dispersion-managed systems the limiting value of the dispersion as a result of amplitude errors is reduced by ξ, which is a major advantage for enhanced-power solitons, since contributions to the timing jitter are proportional to $D^{1/2}$ for the Gordon–Haus effect and to D^2 for the acoustic effect. Recently, there has been a theoretical suggestion that σ_t^2, the variance of the timing jitter as a result of the Gordon–Haus effect for the solitons propagating in these dispersion-managed systems without in-line optical filters, is reduced by ξ.[4] This extra reduction in timing jitter has enormous system implications and may potentially allow for the relaxation of a number of constraints in optical communication systems based on solitons. We have measured the timing jitter in a dispersion-managed system with in-line optical filters. After reducing the formula for the filtered Gordon–Haus jitter by a factor ξ, we obtained good agreement with the measured data, providing experimental evidence of the extra reduction of soliton jitter resulting from a dispersion map.

The experimental setup is described elsewhere.[5] We have four 25-km spans of normal-dispersion fiber ($D = -1.2$ ps/nm km at 1550 nm) followed by a short section (≈ 8 km) of fiber with dispersion in the anomalous regime ($D = +16.5$ ps/nm km at 1550 nm). For the experiments described in this Letter the path-average dispersion is anomalous, $D = 0.15$ ps/nm km. There are four optical amplifiers in the loop to compensate for the losses in the fiber spans, followed by one final amplifier to overcome the loss that is due to the optical bandpass filter, the loop coupler, and the loop switch. There is a single-bandpass filter in the 108-km loop that has a 3-dB bandwidth of ≈ 1.3 nm. With this setup we observed stable pulse propagation up to distances of 28,000 km.[5] For the measurements described in this Letter we used modulated data with both a $2^7 - 1$ and a $2^{23} - 1$ pseudorandom binary sequence (PRBS) pattern at 10 Gbit/s and unmodulated data at a pulse-repetition rate of 10 GHz. For the 10-Gbit/s modulated data we measured a bit-error rate of less than 10^{-9} at a distance of 15,000 km. Figure 1 shows the measured decision voltage threshold for errors (bit-error rate BER $= 1 \times 10^{-6}$) as a function of propagation distance for the $2^{23} - 1$ pattern, noting that the data were essentially the same for the $2^7 - 1$ pattern. We can see from these data that the amplitude of the pulses (1's) is stable as a function of distance while the noise when there are no pulses (0's) is growing because of excess gain.

To measure the timing jitter, we used three different methods to cover the range of propagation out to 20,000 km. First, we used the reduction of the phase margin as a function of distance at a particular deci-

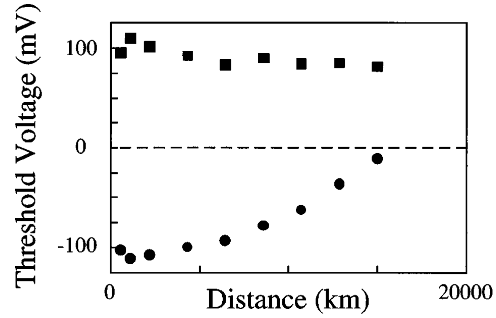

Fig. 1. Measured threshold voltage for a 10^{-6} bit-error rate. The squares are near the 1's, and the circles are near the 0's.

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sion level for BER $= 1 \times 10^{-6}$ to extract the timing jitter, assuming Gaussian statistics. Further, we measured the jitter of the eye with a sampling oscilloscope. Finally, we used unmodulated data, i.e., a pulse train, and we measured the jitter of the pulses with the same sampling oscilloscope. This last procedure eliminates the contribution of the acoustic effect.[6] The results of our measurements are shown in Fig. 2. We note that these measurements yield the same jitter to within approximately 0.25 ps over most of the measurement range. The larger spread of data at short distances of $\leq$4000 km is due to subtraction of the oscilloscope jitter from the data to obtain the jitter in the pulses. The oscilloscope jitter was of the order of 2 ps, and thus small fluctuations in the measurements lead to larger errors at these short distances. These differences become unimportant at larger distances, as is verified by the close agreement among the different techniques at these distances. At distances greater than 15,000 km the errors induced by the energy in the 0's interfere with the measurement of the errors that are due to timing. The bit-error rate measurements rely on the tail of the distributions. The tails of the timing and the amplitude errors begin to overlap at these large distances, making it difficult to separate them and determine the effects of timing errors alone. The oscilloscope measurements, on the other hand, measure the distribution in the vicinity of the peak, where there is essentially no overlap of the distributions out to 20,000 km. For these reasons we did not use the bit-error-rate measurements beyond 15,000 km.

The data in Fig. 2 look remarkably like Gordon–Haus timing jitter modified by a filter.[7,8] To model our system we used the analytic result for the filtered Gordon–Haus effect modified for frequency sliding for solitons propagating in constant-dispersion fiber.[9] The formula that we used from Ref. 9 is of the form $\sigma_{\mathrm{GH}}^2 \times f(\eta, z, \omega')$, where σ_{GH}^2 is the variance that is due to the Gordon–Haus jitter and $f(\eta, z, \omega')$ is the filter-damping function, which is a function the filter strength per unit distance η, the propagation distance z, and the sliding rate ω'.[9]

Reference 4 suggests that σ_{GH}^2 is reduced by ξ for a dispersion-managed system with no optical filters. In the derivation of σ_{GH}^2 a factor of $1/E$, where E is the pulse energy, comes from the relationship between the mean-square amplitude of the noise and the gain of the optical amplifiers.[10] In a dispersion-managed system E is bigger by a factor of ξ. This leads to the reduction of σ_{GH}^2 by the factor of ξ in Ref. 4. Adopting this same strategy, the analytical form for our model is $(\sigma_{\mathrm{GH}}^2/\xi) f(\eta, z, \omega')$. One might question our use of these formulas for ideal solitons, since in simulations of our system we found that the pulse shape and spectrum are quite different from those of ideal solitons.[11] However, as we show below, this model yields an impressive agreement with the experimental data.

For the model shown in Fig. 2 we used σ_{GH}^2 in real world units[3] corrected for the more accurate determination of the nonlinear index of refraction in optical fibers.[12] The experimental parameters that we used for σ_{GH}^2 were loss per unit length $\Gamma = 0.069\ \mathrm{km}^{-1}$, which includes the total loss in our loop including fiber, connections, couplers, filter, and switch; path-average effective area of the fiber, $A_{\mathrm{eff}} = 47\ \mu\mathrm{m}^2$; excess spontaneous emission factor $n_{\mathrm{sp}} = 1.3$; power penalty owing to the variation of soltion amplitude between the optical amplifiers, $F(G) = 1.14$, where $G =$ gain; and path-average dispersion $D = 0.15$ ps/nm km.

The complication in using the analytic formulas in Refs. 3 and 9 is that the pulse shape assumed in these references is an ideal soliton, so that any pulse width used in these formulas corresponds to an ideal soliton. As mentioned above, the simulations of stable pulse propagation in our loop result in nonideal pulse shapes that also have a frequency chirp. In separate experiments we determined that the pulses from our source are $\sim$20 ps in duration, but we are unable to determine the pulse width in the loop to the same degree of accuracy. We observed an $\approx$30% spectral broadening of our input pulse as it propagates through the loop. In the analytic formulas of Refs. 3 and 9 we used a pulse width (FWHM) $\tau_f = 17$ ps. We obtained this pulse width from the steady-state spectrum in the loop ($z > 10{,}000$ km) with the assumption of an ideal Gaussian pulse. This may be a reasonable assumption since the optical filter is sensitive to bandwidth. We use a filter strength $\eta = \zeta/(L_f {\tau_c}^2) = 0.45\ \mathrm{Mm}^{-1}$. Here ζ is the maximum measured filter curvature $\approx 4.5 \times 10^{-24}\mathrm{s}^2$, $L_f = 0.108$ Mm, which is the filter spacing, and $\tau_c = \tau_f/1.762$. For these parameters the ratio of the sliding angular frequency to that of the critical frequency in soliton units is $\omega_f'/\omega_{\mathrm{cr}}' = 0.5$. Figure 2 shows the model without the enhancement factor, $\xi = 1.0$ (dashed line). We chose the value of $\xi = 2.6$ (solid line) in Fig. 2 to give good agreement with the experimental data. This value of the enhancement is in good agreement with the value of $\approx$2.5 obtained from our simulations of the loop.[5,11] Also, we estimated our experimentally determined enhancement factor by measuring the pulse energy in the loop and comparing it with the energy of a soliton of the same pulse

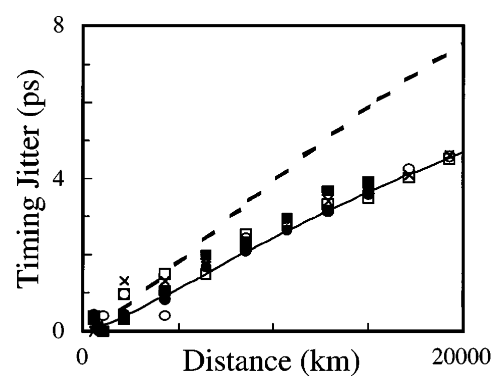

Fig. 2. Timing jitter as a function of propagation distance. For the modulated data the filled and open squares are bit-error-rate measurements and the eye measurements on the oscilloscope, respectively, using a $2^7 - 1$ PRBS pattern; the filled and open circles are bit-error-rate and eye measurements on the oscilloscope, respectively, using a $2^{23} - 1$ PRBS pattern; $\times$'s are an unmodulated pulse train. The lines are the theoretical model with a 17-ps pulse width and an enhancement factor of 1.0 (dashed line) or 2.6 (solid line).

width propagating in a fiber with a constant dispersion equal to our path average, taking into account lumped amplification. The enhancement factor determined this way is approximately 2, which is in reasonable agreement with the factor of 2.6 needed to fit our data in Fig. 2, since we measured the power in our loop after a series of couplers.

Our results indicate that soliton-perturbation theory has application in solitonlike systems such as ours, in which the pulse shapes deviate significantly from the shapes of ideal solitons. These analytical formulas provide a powerful tool for understanding nonlinear pulse propagation in dispersion-managed systems and should aid in the optimization of their design to minimize timing jitter. Our sliding rate is small (1 GHz/Mm), and we see clearly from Fig. 1 that the excess gain is causing the noise accumulation in the 0's, limiting our error-free (BER $< 10^{-9}$) transmission distance to 15 Mm. Our measured timing jitter indicates that the jitter would not limit the error-free bit-error rate for distances less than 20 Mm. By optimizing the enhancement factor, filter design, and path average dispersion, we anticipate that we will further increase the error-free propagation distance.

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