Experimental Demonstration of Soliton Transmission Over 28 Mm Using Mostly Normal Dispersion Fiber

J. M. Jacob, E. A. Golovchenko, A. N. Pilipetskii, G. M. Carter, and C. R. Menyuk

***Abstract*—We report on stable soliton propagation experiments in a fiber transmission system consisting of more than 90% normal dispersion fiber. The transmission system has a dispersion map much like that used in nonreturn-to-zero (NRZ) pulse transmission but with a path-average anomalous dispersion of $+0.1$ ps/nm–km. A stable soliton pulse train at 8 GHz has been observed after 28 Mm of propagation in a 108-km recirculating fiber-optic loop. A significant enhancement in the average soliton power required for stable transmission in a dispersion map with alternating signs of dispersion is experimentally demonstrated for the first time. Theoretical modeling of our experiment is in good agreement with our findings.**

***Index Terms*—Solitons, long-distance optical communications, dispersion management.**

DISPERSION MANAGEMENT in long-haul soliton communication systems can be employed as a technique for improving systems performance [1]–[4]. The dispersion maps consist of alternating lengths of fiber having positive (anomalous) and negative (normal) dispersion, D[ps/nm–km]. The principal idea is to maintain a high value of local dispersion but allow for a low value of average dispersion. It has recently been shown in a theoretical model that maps with alternating signs of the local dispersion and a given average dispersion require an enhanced soliton power in comparison to a map with uniform dispersion equal to that average [1]. Therefore, with dispersion maps it is possible to reduce timing jitter by using the low average dispersion and maintaining significant pulse energy to avoid errors caused by amplitude fluctuations.

In the theoretical work of [1] and [2], the dispersion maps consisted of no more than 50% normal dispersion fiber. The experiments in [3] used dispersion maps in which the length of normal dispersion fiber was less than 1% of the total map. In this letter, we clearly demonstrate, experimentally for the first time, that it is possible to transmit a stable soliton pulse train using a dispersion map in which greater than 90% of the map uses normal dispersion but in which the path-average dispersion is anomalous. As a consequence, the effects of four wave mixing on single pulse propagation are reduced. Stable transmission of an 8-GHz soliton pulse train over 28 Mm was observed in a 108 km recirculating fiber loop experiment. We also give the first experimental evidence of the enhanced soliton power required for stable transmission using dispersion management. A similar dispersion map was recently modeled in [4].

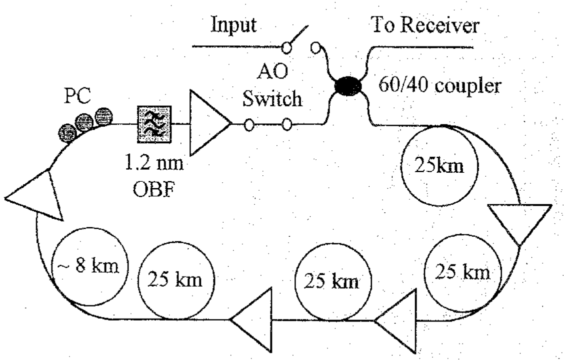

Fig. 1. Schematic of 108 km recirculating fiber-optic loop. The dispersion map consists of 4×25 km of normal dispersion ($D = -1.2$ ps/nm–km) fiber and 8 km of anomolous dispersion ($D = +16.5$ ps/nm–km) fiber.

Our transmission system is a recirculating fiber-optic loop consisting of four amplifier spans as shown in Fig. 1. Each of the first three spans contains 25 km of dispersion-shifted fiber with a normal dispersion of -1.2 ps/nm–km at 1550 nm. The fourth span consists of 25 km of the same dispersion shifted fiber followed by $\sim$8 km of standard fiber with an anomalous dispersion of $+16.5$ ps/nm–km at 1550 nm. By varying the length of the standard fiber, the path-averaged dispersion can be chosen to lie in the normal or anomalous dispersion regime. This dispersion-management scheme is similar to that used in NRZ transmission with average normal dispersion [5]. The stable soliton transmission in the average anomalous dispersion regime suggests a simple recirculating loop design that can be easily modified for NRZ or soliton transmission experiments.

The recirculating loop has five variably spaced EDFA's with a spontaneous emission factor between 1.4 and 1.7. The first three EDFA's have gain $\cong$5.5 dB to account for the loss in the 25-km fiber span. The fourth EDFA has gain $\cong$9 dB to account for loss in the 25 km + 8 km fiber span as well as provide excess gain to the optical bandpass filter (OBF). The final EDFA has gain $\cong$7 dB to account for loss in the AO loop switch and coupler. The acoustooptic (AO) switches shift the optical frequency by $+100$ MHz. The optical bandpass filter has a FWHM of 1.2 nm. A single polarization controller is used to minimize the polarization-dependent

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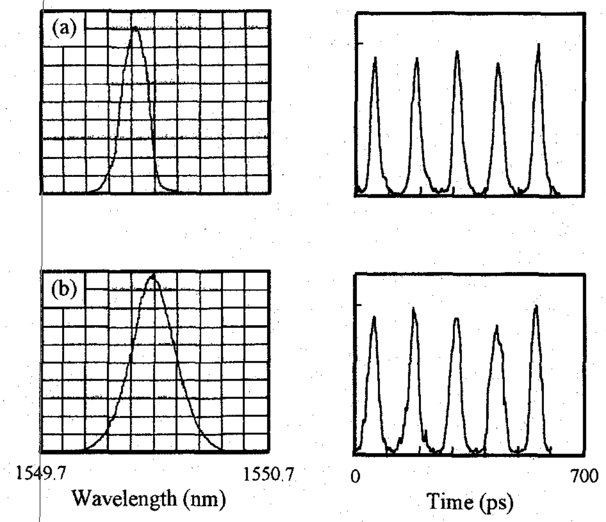

Fig. 2. Optical spectrum and pulse trains for (a) loop input and (b) 28 Mm propagation with $D_{\mathrm{avg}} = +0.1$ ps/nm–km.

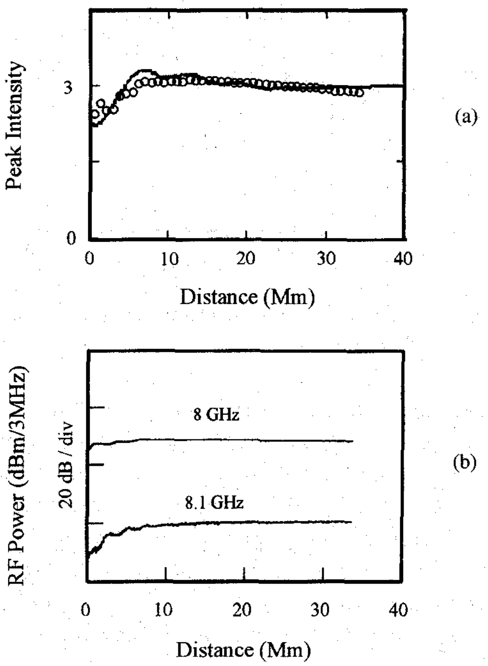

Fig. 3. (a) Peak intensity from computer modeling (solid line) and measured 8-GHz fundamental RF component (open circles) versus propagation distance. (b) Signal (8 GHz) and noise (8.1 GHz) characteristics of transmission system.

effects in the loop [6]. The input pulse train is generated from a spectrally-filtered, phase-modulated CW laser capable of producing pulses from 6–12 GHz with 20–40 ps FWHM [7], [8]. In this experiment, the input signal was a pulse train at 8 GHz with a FWHM pulse duration $\cong 30$ ps. The optical pulse train was measured using a streak camera with a temporal resolution of 2 ps.

The optical spectrum and pulse train are shown in Fig. 2 for (a) the input and (b) 28 Mm of propagation. The 28-Mm limit is that of an electrical delay line used for instrument gating and not due to the soliton transmission. The soliton pulse train shows no significant distortion after 28 Mm transmission which suggests that timing jitter and amplitude fluctuations are low in our experiments. Fig. 2 shows significant spectral broadening of the pulses between input and 28 Mm. A detailed study of the evolution shows that the shape evolves between 0 and 10 Mm and then remains unchanged. This behavior is due to a complex interplay between the optical bandpass filter, the AO frequency shifting, and the dispersion map. The combination of the AO loop switch and the optical bandpass filter results in a frequency sliding rate of 1 GHz/Mm [9], in contrast to the 6–12 GHz/Mm sliding rates used in other loop experiments [10]–[13]. While the sliding rate is lower in real world units, the low average dispersion of the map that we are using implies that the guiding imposed by the filter is still strong in soliton units [14]. As a consequence, the resulting pulse shape and spectrum displays slight asymmetric features, as predicted by our model. This distinctly differs from the Guassian shapes discussed in [1], which did not consider the effects of filtering and frequency sliding. We will discuss in detail the combined effects of spectral filtering, optical frequency shifting, and the dispersion map based on our theoretical modeling in a forthcoming article.

Fig. 3 demonstrates some of the observed effects due to the spectral filtering, optical frequency shifting, and the dispersion map. In Fig. 3(a), the solid line is the peak intensity versus distance calculated in our model based on the experimental parameters. The open circles are power measurements of the 8-GHz fundamental RF component from the optical pulse train which is in excellent agreement with the predicted peak intensity. The pulse reaches equilibrium after 10 Mm of propagation. The optical bandpass filter has an important role in the equilibrium of the pulse propagation as can be seen when compared to our model without filtering [15]. The model predicts that the peak intensity at equilibrium is three times that of a fundamental soliton in a uniform dispersion transmission system with $D = +0.1$ ps/nm–km. In our experiments the average optical power measured at 28 Mm is -3.8 dBm. Accounting for fiber loss, the experimental power is approximately a factor of 3.5 times larger than what is expected for a fundamental 30 ps soliton in an unfiltered, uniform dispersion system. Our model shows that about 70% of the enhancement factor is due to the dispersion map and 30% is due to spectral filtering plus frequency shifting.

Fig. 4 shows the evolution of the equilibrium pulse width within the dispersion map. Over the first 100 km of normal dispersion fiber, the pulse slowly broadens to nearly 1.4 times the input width because the magnitude of the dispersion is small. During the next 8 km of anomalous dispersion fiber, the pulse rapidly compresses to its initial pulse width because the magnitude of the dispersion is large. This phenomenon is similar to what appears in stretched-pulse fiber ring lasers using alternating positive and negative dispersion fibers [16]. The increased pulsewidth over much of the dispersion map leads to the enhanced power requirement for stable transmission.

Fig. 3(b) shows the measured SNR properties of our system over 35 Mm of propagation. The stability of the 8-GHz optical pulse stream is demonstrated by the measured power of the fundamental RF component, and the noise accumulation measured at 8.1 GHz. The noise increases exponentially for the first few thousand kilometers before stabilizing at a constant

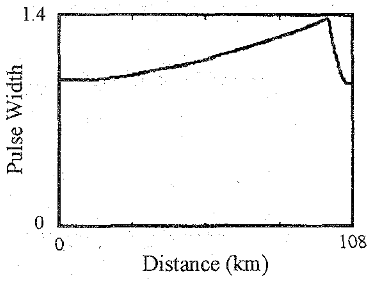

Fig. 4. Computer simulation of equilibrium pulse width evolution over one dispersion map cycle at 40 Mm.

level, demonstrating that the frequency shift and spectral filter, coupled with low path–average dispersion efficiently reduces noise accumulation. Preliminary bit-error rate measurements of a $2^{15}-1$ PRBS at 10 Gb/s have verified error-free transmission up to 10 Mm. We are presently investigating the cause of the 10-Mm limit. However, based on our model and the results presented here, we believe that 10 Gb/s error-free transmission exceeding 10 Mm is promising in our proposed dispersion map.

In conclusion, we have experimentally demonstrated for the first time enhanced power, stable soliton transmission up to 28 Mm using a dispersion map which contains more than 90% normal dispersion fiber.

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