Experimental Demonstration of Long-Distance Dispersion-Managed Soliton Propagation at Zero Average Dispersion

V. S. Grigoryan, R.-M. Mu, G. M. Carter, and C. R. Menyuk

***Abstract*—We observed for the first time stable propagation of dispersion-managed solitons with zero or slightly normal average dispersion over 28 000 km in a recirculating fiber loop. Comparison between theory and experiment provides a highly sensitive estimate of the average dispersion.**

***Index Terms*—Optical fiber communication, optical fiber dispersion, optical propagation in nonlinear media, optical solitons.**

I. Introduction

ONE OF the major sources of errors in soliton systems is timing jitter. It is possible to greatly reduce the timing jitter by using dispersion-managed solitons (DMS) with low path average dispersion [1], [2]. A number of authors have shown theoretically in the past year [3]–[8] that it is possible to propagate DMS pulses at zero average dispersion. The timing jitter in this case is almost completely eliminated. It has been shown also [3]–[8] that it is even possible to propagate DMS pulses with net normal average dispersion; however, it is difficult in practice to experimentally observe DMS pulses with zero or net normal average dispersion. As the average dispersion $\overline{D}$ changes its sign from anomalous to normal, the stretching factor of the DMS pulses significantly increases, leading to interpulse interference. Moreover, for peak powers on the order of milliwatts, DMS pulses can only exist in a narrow range of normal $\overline{D}$ on the order of 0.01 ps/nm·km.

In this letter, we present the first experimental observation of DMS propagation at zero average dispersion. We observed the propagation of a continuous 10-GHz pulse train in a recirculating loop over 28 000 km. We used the same recirculating loop and dispersion map reported in [9]. The dispersion map consists of 100 km of dispersion-shifted fiber (DSF) with a normal dispersion of −1.2 ps/nm-km followed by about 7 km of standard fiber with an anomalous dispersion of +16.7 ps/nm-km, the amplifier spacing is 25 km. We use an optical band-pass filter with FWHM of 2.8 nm in the loop. Tuning the wavelength of the source allowed us to smoothly cross the point $\overline{D} = 0$. We developed a model of the experiment that takes into account all the major mechanisms affecting the pulse evolution, they are the second- and third-order dispersion, Kerr nonlinearity, the amplified spontaneous emission (ASE) noise and gain saturation in the erbium-doped amplifiers. In the model the optical bandpass filter has a Gaussian shape. We used the rate equation for the erbium-doped fiber amplifiers (EDFA's) [10] to describe the dynamics of the saturated gain in time. Details of the model can be found in [11]. The model allowed us to study evolution of an initial pulse through an initial transient regime into the periodically stationary regime. Fig. 1 shows the dynamics of the pulse duration inside the loop in the periodically stable regime predicted by our model. One can see that when $\overline{D} = -0.01$ ps/nm·km, the stretching factor is several times larger than when $\overline{D} = 0.04$ ps/nm-km. The limiting value of $\overline{D}$ for our parameters is about –0.015 ps/nm·km. We observed propagation up to a limit of $\overline{D} = -0.005 \pm 0.005$ ps/nm·km. The dispersion was determined by measuring the phase difference between two RF-modulated light waves, a reference wave and a probe wave. The wavelength of the reference wave was fixed. Tuning the wavelength of the probe wave we were able to measure the dependence of the phase difference on wavelength. The minimum of the phase difference corresponds to zero-average dispersion.

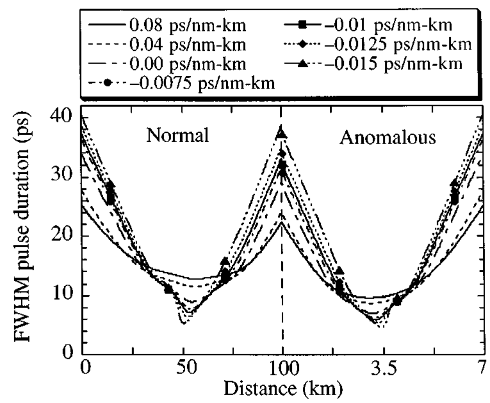

Fig. 1. Theoretical dependence of the pulse duration of the DMS on distance inside the fiber loop at different $\overline{D}$. We measure distance separately, on different scales for the normal and anomalous spans.

To check stable propagation of the 10-GHz DMS pulse train, we monitored the intensity of the 10-GHz RF component, also referred to as the first RF tone using a technique analogous to that reported in [12]. As we will show, not only does this approach allow us to accurately monitor the decay of the solitons as interpulse interference and the background ASE noise grows, but in conjunction with the theory allows us to sensitively determine the average dispersion. This approach indicates that our limiting value of $\overline{D}$ is –0.01 ps/nm·km, somewhat below the theoretical limit. We may write the intensity $I(z, t)$ in a train of N

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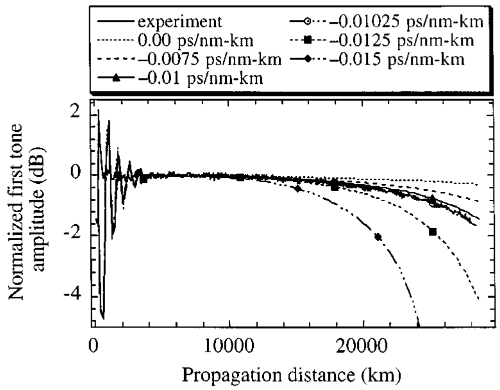

Fig. 2. Degradation of the first tone intensity of the DMS pulse train detected at the midpoint of the anomalous dispersion span as a function of propagation distance. The solid line without marks shows our experimental data, while the other lines show theoretical predictions at different values of $\overline{D}$. Note that the experimental data lies almost exactly on the theoretical curve $\overline{D} = -0.010\,25$ ps/nm·km.

pulses as $I(z, t) = \sum_{k=1}^{N} I_k(z, t - kT_0)$, where z is propagation distance in the loop, t is time, T_0 is the bit period, and I_k is the intensity of kth pulse in the train. We then find that the intensity of the 10-GHz frequency component is given by

$$I^{(1)}(z) = \frac{1}{T_0} \left| \int_{-T_0/2}^{T_0/2} \overline{I}(z, t) \exp(2\pi i t/T_0)\, dt \right| \tag{1}$$

where

$$\overline{I}(z, t) = (1/N) \sum_{k=1}^{N} I_k(z, t).$$

Since the DMS is concentrated near the center of the bit window, $I^{(1)}(z)$ is initially only slightly smaller than the total intensity. However, as z increases and the DMS signal degrades due to the growth of ASE noise and interpulse interference, the energy becomes spread through the bit window, and $I^{(1)}(z)$ tends to zero. Fig. 2 shows the normalized first RF tone versus distance from both theory and experiment. Stationary propagation follows about 2000 km of propagation in the transient regime. Theory shows that as $\overline{D}$ becomes increasingly negative beyond $\overline{D} = -0.01$ ps/nm·km the propagation distance of the DMS rapidly decreases due to dramatic increase of the stretching factor shown in Fig. 1. At $\overline{D} = -0.01$ ps/nm·km, degradation of the relative amplitude of the first tone at 28 000 km is only 1.5 dB. However,when $\overline{D} = -0.0125$ ps/nm·km, the first tone rapidly decreases beyond a distance of about 20 000 km, and when $\overline{D} = -0.015$ ps/nm·km, it rapidly decreases beyond a distance of about 10 000 km. Thus, the comparison between theory and experiment provides a very sensitive measurement of $\overline{D}$, indicating that $\overline{D}$ nearly equals –0.01 ps/nm·km. This value is consistent with our direct experimental measurement that $\overline{D} = -0.005 \pm 0.005$ ps/nm·km. It is difficult to make accurate, direct measurements of $\overline{D}$ below the level of 0.01 ps/nm·km, which accounts for the relatively large error bars.

In conclusion, we have observed for the first time stable propagation of a dispersion-managed soliton with zero or slightly normal average dispersion $\overline{D}$ over 28 000 km in a recirculating loop. Comparison between theory and experiment provides a highly sensitive estimate for $\overline{D}$.

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