Periodic dispersion management in soliton wavelength-division multiplexing transmission with sliding filters

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We compare the performance of dispersion-managed fibers with that of dispersion-decreasing fibers and of fibers with uniform dispersion in filtered soliton wavelength-division multiplexing transmission. Alternating-sign dispersion management allows us to achieve values of collision-induced timing jitter that are comparable with what can be achieved by use of dispersion-decreasing fiber and are lower for some parameter values.

The use of in-line guiding filters together with frequency sliding has proved to be an extremely efficient technique for high-performance soliton transmission.[1,2] Moreover, Fabry–Perot étalons as in-line sliding filters can be naturally combined with wavelength-division multiplexing (WDM), with the channel spacing determined by the filter free-spectral range.[2,3] A major source of errors in soliton WDM transmission is collision-induced timing jitter.[4] An unfavorable resonant case happens when the collision distance of pulses in different spectral channels is equal to the amplifier spacing. In this case the solitons acquire large residual frequency shifts after a collision, which in turn leads to a significant enhancement of the timing jitter. Moreover, soliton collisions create four-wave-mixing fields that alter the soliton amplitudes and frequencies.[2] A possible way to improve the soliton WDM system performance is to use either dispersion-decreasing fiber[5] or alternating-sign dispersion maps.[6] The use of dispersion-decreasing fiber can help to reduce the four-wave-mixing fields in WDM and remove the residual frequency shifts, thus relaxing the resonant condition.[5] Alternating-sign dispersion management was discussed as a possible way to suppress soliton instabilities in filtered WDM,[6] and it was recently shown as well that alternating-sign dispersion management can significantly reduce the timing jitter in an unfiltered WDM system.[7]

In this Letter we study WDM soliton transmission in a system with Fabry–Perot sliding filters and compare the performance of systems that are based on a uniform-dispersion fiber, a dispersion-decreasing fiber, and a periodically dispersion-managed fiber. We show that periodic alternating-sign dispersion management can reduce the effects of both the resonant soliton collisions and the four-wave-mixing fields. Such a technique is a feasible alternative to dispersion-decreasing fiber in improving the performance of a WDM system and is simpler to implement.

We have simulated as many as eight WDM soliton channels in an optical fiber with lumped amplification and filtering. Each channel is filled with pseudorandom 32-bit sequences of 20-ps solitons and operates at 10 Gbits/s. The simulations used a split-step method to solve the nonlinear Schrödinger equation. The path-averaged dispersion was $D = 0.5$ ps/nm km, and the amplifier spacing was 40 km. In the filtered transmission system we used Fabry–Perot étalons with a reflection coefficient $R = 0.09$ and with a free-spectral range equal to the channel spacing at the same location as the amplifiers, and we shifted the filter transmission frequency along the propagation distance at a rate equal to 0.45 of the critical sliding rate (3.3 GHz/Mm).[1] We assumed that the amplifiers compensate ideally for the fiber and filter losses to maintain 20-ps pulses. Because we were investigating the timing jitter from soliton collisions, we did not include spontaneous emission noise from the amplifiers. We studied a fiber with uniform dispersion, a dispersion-decreasing fiber with an ideal exponential taper, and a periodically dispersion-managed fiber with the sign of the dispersion changing between the amplifiers. The dispersion map that we used in our calculations consisted of a 35-km fiber with normal dispersion, $D_1 = -2$ ps/nm km, followed by a 5-km fiber with anomalous dispersion, $D_2 = 18$ ps/nm km, to provide an average anomalous dispersion of $D = 0.5$ ps/nm km. The total length of the dispersion map equaled the amplifier spacing. It should be mentioned that the dispersion scheme was not long enough to require power-enhanced solitons,[8] so the path-averaged power of the solitons was approximately the same in all cases.

First, to investigate the effects of soliton–soliton collisions on data transmission in the different dispersion schemes, we simulated the collisions of a single soliton in one channel with a pseudorandom sequence of solitons in a channel downshifted in frequency by 210 GHz (or 1.68 nm). We started with a comparison between the collisions in filtered and unfiltered systems. Figures 1 and 2 show the frequency deviations of a soliton in one channel that is experiencing collisions with randomly placed solitons in the other channel. Figure 1 shows the unfiltered system, and Fig. 2 shows a system with sliding filters. The length of the collision in this case is 47 km, which is close to the amplifier spacing, so the collisions are resonant. Without dispersion management, the soliton has large residual frequency deviations after the collisions. Dispersion-decreasing fibers eliminate completely the residual

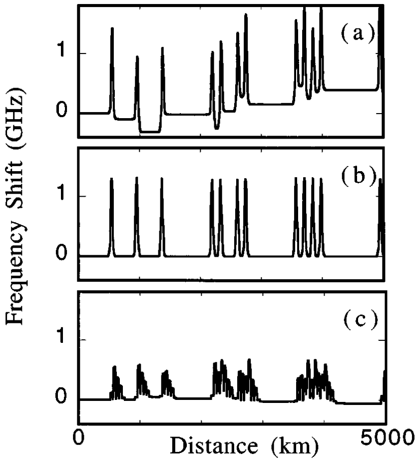

Fig. 1. Frequency deviation of a soliton that is colliding with a random data stream in a frequency channel downshifted by 210 GHz in an unfiltered system for (a) uniform-dispersion fiber, (b) dispersion-decreasing fiber, and (c) dispersion-managed fiber. The collision length is 47 km.

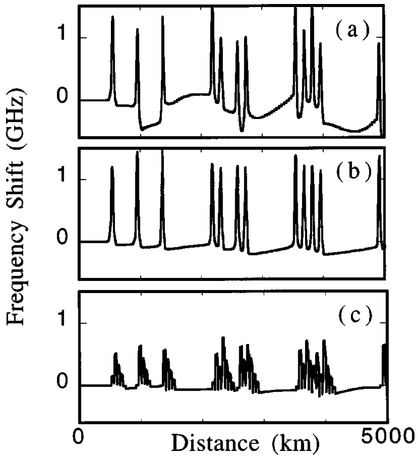

Fig. 2. Frequency deviation of a soliton that is colliding with a random data stream in a frequency channel downshifted by 210 GHz in a system with sliding filters for (a) uniform-dispersion fiber, (b) dispersion-decreasing fiber, and (c) dispersion-managed fiber. The collision length is 47 km.

frequency shifts in an unfiltered system (Fig. 1), and they reduce the shifts significantly in a system with an alternating-sign dispersion map because the value of a soliton frequency offset oscillates many times during the collision owing to the alternating sign of the dispersion. The collison occurs over a longer length than in the case for either uniform-dispersion or dispersion-decreasing fibers, thus reducing the absolute value of the frequency offset and relaxing the resonant condition on the amplifier spacing. The reason for the increased length is that the large temporal oscillations of the soliton whose frequency shifts we are studying mean that the collision begins and ends when on average the colliding solitons are well separated. This effect is clearly visible in Figs. 1 and 2. We conclude that the collision-induced timing jitter can be significantly reduced not only in systems with dispersion-decreasing fibers but also in alternating-sign dispersion fibers.

A guiding filter changes the nature of the collision. As shown in Fig. 3(a), a soliton in an unfiltered system undergoes time shifts, which accumulate regardless of the dispersion map, whereas as shown in Fig. 3(b) filters induce a residual frequency shift that tends to compensate for the time shift during the collision. In fact, this compensation is complete in a system with distributed filters,[9] but it is not complete in our system, which contains lumped filters, as is visible in Fig. 3(b). In Fig. 3(b) we show a case in which the residual time shift is larger for the dispersion-managed fiber than for the dispersion-decreasing fiber. In fact, consideration of a large number of different cases shows that the time shifts are statistically comparable, as we now discuss.

To evaluate the performance of a WDM system we simulated the propagation of data streams in as many as eight spectral channels. To reduce the initial partial collision, the soliton sequences in neighboring channels were shifted by half a time slot. We found that for a single channel the transmission characteristics do not depend on the type of dispersion management. Our calculations have shown that when the sliding rate is close to critical the timing jitter is considerably larger than for moderate sliding rates, consistent with the theory in Refs. 1 and 10.

Figure 4 shows the calculated standard deviation of the timing jitter, σ, versus transmission distance for an eight-channel WDM system with channels spaced six pulse spectral widths (105 GHz) apart, for different types of dispersion management. The simulations show that with upsliding filters the lower-frequency channels experience more impairment than do the higher-frequency channels. This asymmetry occurs because pulses in channels with lower frequencies experience collisional frequency shifts mainly in the direction opposite the filter frequency sliding. Dispersion-managed fibers induce less asymmetry in the performance of lower- and higher-frequency channels because the absolute frequency shifts of solitons during the collisions are smaller. Because collisions occur over longer lengths for dispersion-managed

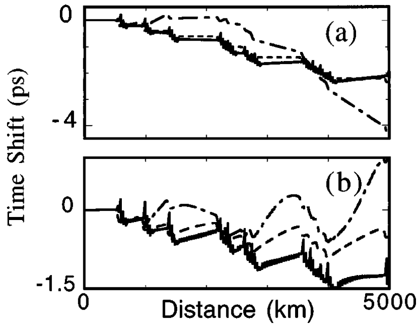

Fig. 3. Relative time shifts of a soliton owing to collisions with a random data stream in a frequency channel downshifted by 210 GHz for (a) an unfiltered system (b) a filtered system with dispersion-managed fiber (solid curve), dispersion-decreasing fiber (dashed curve), and uniform-dispersion fiber (dotted–dashed curve). Parameters are the same as in Figs. 1 and 2.

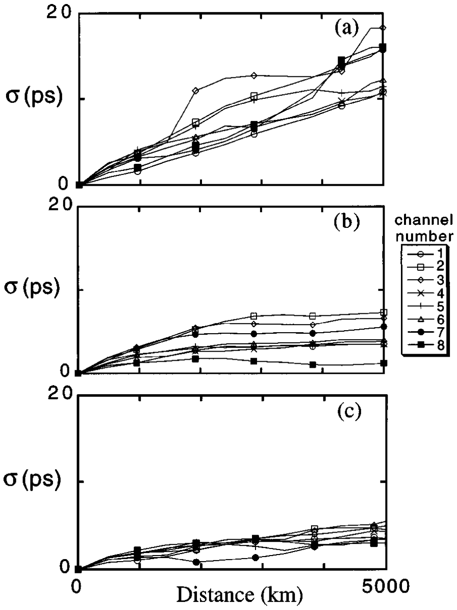

Fig. 4. Standard deviation of jitter in soliton arrival times versus propagation distance for an eight-channel WDM system with sliding filters for (a) uniform-dispersion fiber, (b) dispersion-decreasing fiber, and (c) dispersion-managed fiber. The collision length of the neighboring channels is 94 km, which is larger than two amplifier spacings, and the sliding rate is 3.3 GHz/Mm. Channel number 1 corresponds to the lowest frequency.

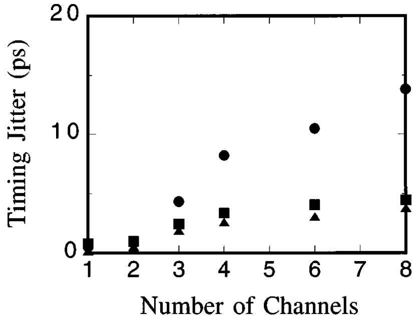

Fig. 5. Average timing jitter in soliton arrival times versus the number of frequency channels in a soliton WDM system with sliding filters at $z = 5000$ km based on uniform-dispersion fiber (circles), dispersion-decreasing fiber (squares), and dispersion-managed fiber (triangles). The collision length of the neighboring channels is 94 km, and the sliding rate is 3.3 GHz/Mm.

solitons, the filter compensation is better for the collision-induced timing jitter. Figure 5 shows the timing jitter averaged over all the channels as a function of the number of channels when the channels are spaced by six pulse spectral widths (105 GHz). The system with dispersion-managed fiber has slightly better performance than the system with dispersion-decreasing fiber, which in turn performs much better than the system with uniform-dispersion fiber. The large difference between a system with three or more channels and a two-channel system is due to the three-soliton collisions,[11] which create four-wave-mixing fields that alter the soliton frequencies and cause an energy exchange between the channels.

It should be noted that the parameters of the systems that we have studied are not necessarily optimal. For our parameters the estimate for the Gordon–Haus timing jitter gives the value $\sigma_{\mathrm{GH}} = 3.1$ ps for $n_{\mathrm{sp}} = 1.5$, and $Z = 5$ Mm. Thus the collision-induced timing jitter is the dominant source of jitter in the WDM system that we studied.

Our results indicate that in a system with sliding filters the timing jitter of the dispersion-managed solitons is comparable with the timing jitter of solitons in a fiber with an ideal, exponentially tapered dispersion and can even be less. We also point out that it is easier to construct a dispersion-managed system that it is to construct a system with an ideal, dispersion-decreasing exponential taper. Moreover, it should be possible to operate with lower average dispersion. We conclude that dispersion management is a highly promising technology for WDM soliton transmission.

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