Reduction of soliton interactions by zigzag-sliding-frequency guiding filters

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Reductions of the soliton interactions and jitter by the upsliding-frequency filter, the downsliding-frequency filter, and the zigzag-sliding-frequency filter are numerically studied. It is shown that the most effective filter for reducing the soliton interactions is the zigzag-sliding-frequency filter.

In long-distance soliton communication systems with optical amplifiers used to compensate for the fiber loss, the soliton–soliton interaction and noise-induced timing jitter limit the bit rate. To reduce the soliton interaction and timing jitter, an optical bandpass filter is inserted after every optical amplifier.[1,2] With the filter, the center frequency of the soliton spectrum experiences more gain than the other parts. This leads to stabilization of the carrier frequency and the group velocity of the soliton. Furthermore, it is found that if the center frequency of the filter is slowly sliding with the distance along the fiber, the reductions of the soliton interaction and timing jitter are better than those with the filter of fixed center frequency.[3,4] Such a filter is called a sliding-frequency filter (SFF). In this Letter we show the effects of the downsliding-frequency filter (DSFF) and the upsliding-frequency filter (USFF) on the soliton, where the center frequency of the filter decreases and increases, respectively, along the fiber. Numerical calculations show that a slightly dispersive wave is generated and enhances the soliton interaction when the DSFF or USFF is used, since the soliton spectrum cannot adiabatically follow the SFF. Therefore, by using the zigzag-sliding-frequency filter (ZSFF) of which the center frequency of the ZSFF is alternately upsliding and downsliding along the fiber, we can effectively reduce the soliton interaction and greatly increase the transmission distance, even when we consider the soliton interaction and spontaneous emission noise simultaneously.

The wave equation that describes a soliton transmitting in a single-mode fiber can be described by the modified nonlinear Schrödinger equation

$$i\frac{\partial U}{\partial z} - \frac{1}{2}\beta_2\frac{\partial^2 U}{\partial \tau^2} - i\frac{1}{6}\beta_3\frac{\partial^3 U}{\partial \tau^3} + n_2\beta_0|U|^2U - c_rU\frac{\partial}{\partial \tau}|U|^2 = -\frac{1}{2}i\alpha U\,, \quad (1)$$

where β_2 and β_3 represent the second-order and third-order dispersions, respectively, n_2 is the Kerr coefficient, c_r is related to the slope of the Raman gain profile, and α is the fiber loss. The coefficients in Eq. (1) are taken as $\beta_2 = -0.57\ \mathrm{ps^2/km}$ [0.45 ps/(km nm)], $\beta_3 = 0.075\ \mathrm{ps^3/km}$, $n_2 = 3.2 \times 10^{-20}\ \mathrm{m^2/W}$, $c_r = 3.8 \times 10^{-16}$ ps m/W, and $\alpha = 0.22$ dB/km. The effective fiber cross section is 35 $\mu\mathrm{m}^2$. The amplifier spacing is $L_a = 50$ km and the soliton pulse width is $T_W = 20$ ps. The transfer function of the optical filter placed after every amplifier is taken as

$$H(\Omega - \Omega_f) = \frac{1}{1 + i\dfrac{2}{B}(\Omega - \Omega_f)}\,, \quad (2)$$

where $\Omega = \omega - \omega_0$ and ω_0 is the original soliton carrier frequency, Ω_f is the center frequency of the filter, and B is the filter bandwidth. For the SFF, Ω_f varies along the fiber. In this Letter the filter bandwidth is taken to be $B/2\pi = 125$ GHz.

We consider the transmission of a soliton pair with a 4-pulse-width separation to show the soliton interaction. Figures 1(a) and 1(b) show the evolutions of the soliton pair along the fiber with the DSFF (−4 GHz/Mm) and USFF (4 GHz/Mm), respectively.

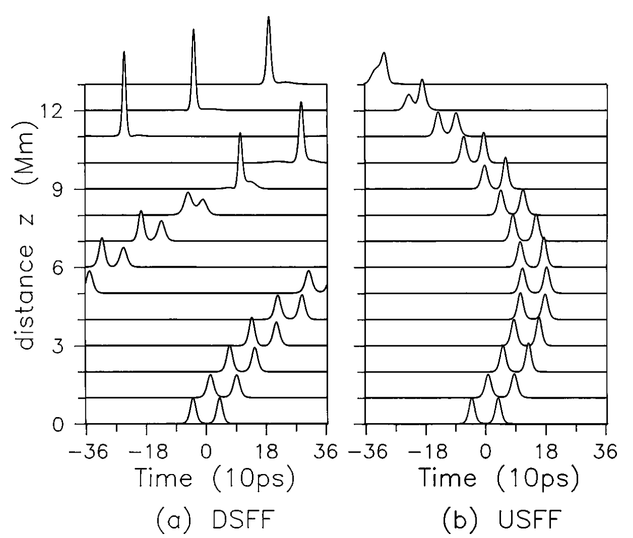

Fig. 1. Evolution of the power envelopes of the soliton pair along the fiber with (a) the DSFF and (b) the USFF.

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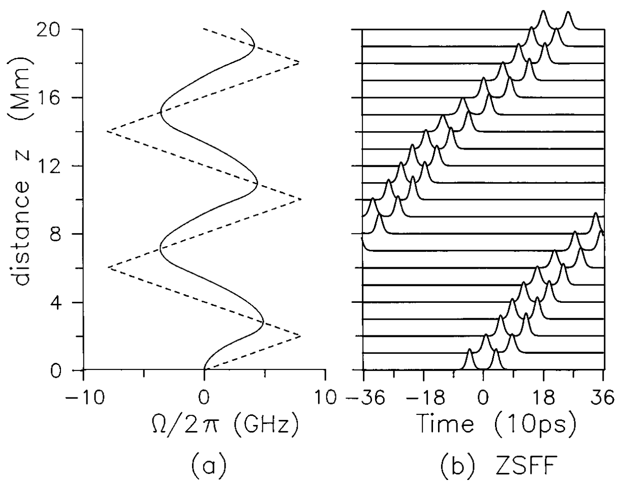

Fig. 2. Center frequencies of the filters Ω_f (dashed line) and the frequency deviation $\Delta\Omega$ (solid curve). (b) Evolution of the power envelope of the soliton pairs with the ZSFF as shown in (a).

One can see that the solitons coalesce at approximately 9 and 13 Mm for the downsliding and upsliding cases, respectively. In contrast, with the fixed center frequency filter the coalescence distance is approximately 7.4 Mm and without the filters the coalescence distance is only approximately 6.0 Mm. The upsliding case is better than the downsliding case because of the dispersion change. When the dispersion length $L_D = (T_W/1.763)^2/\beta_2$ is much larger than the amplifier spacing L_a, the effect of the filter on the soliton transmission can be assumed to be distributed along the fiber.[4] Thus it is easy to derive the effective second-order dispersion experienced by the soliton as

$$\beta_{2\text{eff}} = \beta_2 + \beta_3\Delta\Omega + \beta_{3f}(\Omega_f - \Delta\Omega), \quad (3)$$

where $\Delta\Omega$ is the deviation of the soliton carrier frequency from its original frequency and $\beta_{3f} = 48/3B^3L_a$ is the third-order dispersion introduced by the filter. For the cases shown above, $\beta_{3f} = 0.66\ \text{ps}^3/\text{km}$ is much larger than β_3. As the soliton spectrum is pushed by the SFF, the soliton carrier frequency is behind the center frequency of the filter, and $|\Omega_f| > |\Delta\Omega|$. Because β_2 is negative and both β_3 and β_{3f} are positive, from Eq. (3), for the downsliding case ($\Delta\Omega < 0$ and $\Omega_f - \Delta\Omega < 0$) the effective dispersion $|\beta_{2\text{eff}}|$ increases and the solitons tend to broaden; for the upsliding case ($\Delta\Omega > 0$ and $\Omega_f - \Delta\Omega > 0$) the effective dispersion $|\beta_{2\text{eff}}|$ decreases and the solitons tend to narrow. Thus the soliton pulse width for the case with the USFF is less than that for the case with the DSFF, and the difference in the soliton pulse width for DSFF and USFF increases with the transmission distance.

In the following we consider the case with the ZSFF, where Ω_f is shown by the dashed line in Fig. 2(a) and the sliding rate is +4 GHz/Mm where the frequency is upsliding and −4 GHz/Mm where the frequency is downsliding. The dashed line is a periodic function of propagation distance; the zigzag period is 8 Mm in this case. In Fig. 2(a) the solid curve shows $\Delta\Omega$ for the case with a single soliton transmitting along the fiber with the ZSFF. Figure 2(b) shows the evolution of the soliton pair along the fiber with this ZSFF. One can see that the soliton separation is well maintained, even after 20-Mm transmission. The soliton separation is stabilized because the ZSFF alternately changes the sign of the relative frequency of the two solitons along the fiber. Figure 3 shows the relative frequencies Ω_r of the two solitons for the cases shown in Figs. 1 and 2(b), where Ω_r is the frequency of the soliton initially at $\tau = 40$ ps with respect to the frequency of the soliton initially at $\tau = -40$ ps. One can see that, for the cases with the DSFF and the USFF, Ω_r is positive along the fiber and the two solitons come closer along the fiber and coalesce, whereas for the case with the ZSFF Ω_r is smaller and alternately changes its sign along the fiber. Therefore, with the ZSFF, the soliton separation is stabilized and the soliton interaction is significantly reduced. We now consider the influences of the filter sliding rate and the zigzag period on the soliton transmission. Usually in experimental studies the unidirectional SFF with a sliding rate of 4–6 GHz/Mm is used. Figure 4 shows two pulse separations along the transmission distance with the ZSFF at a sliding rate of ±4 GHz/Mm in which the

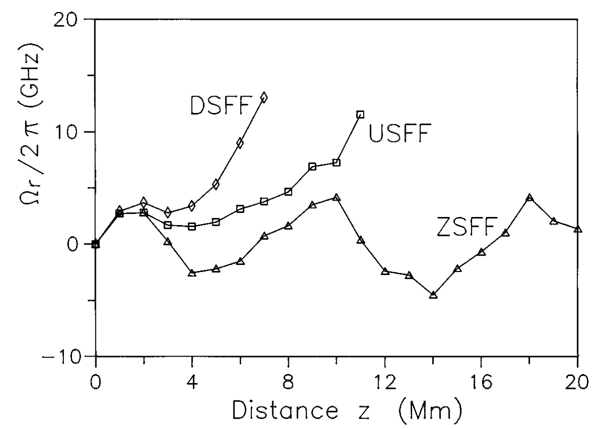

Fig. 3. Evolution of the relative frequency Ω_r of a soliton pair transmitting along the fiber with the DSFF, USFF, and ZSFF.

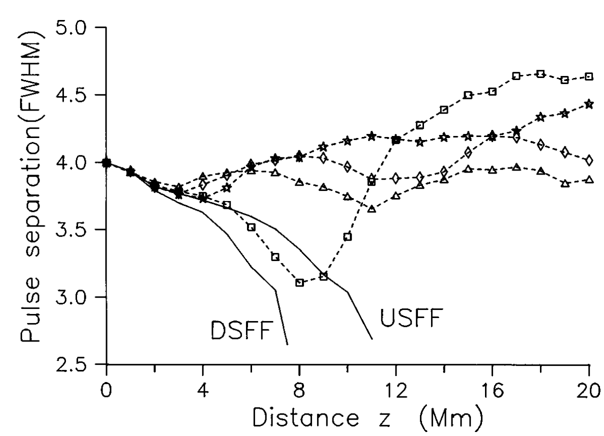

Fig. 4. Pulse separation along the fiber transmission line with a sliding rate of ±4 GHz and a zigzag period of 6 (□), 8 (△), 9 (◇), and 11 (☆) Mm. The pulse separations with the USFF and the DSFF at a sliding rate of 4 GHz/Mm are also shown for comparison.

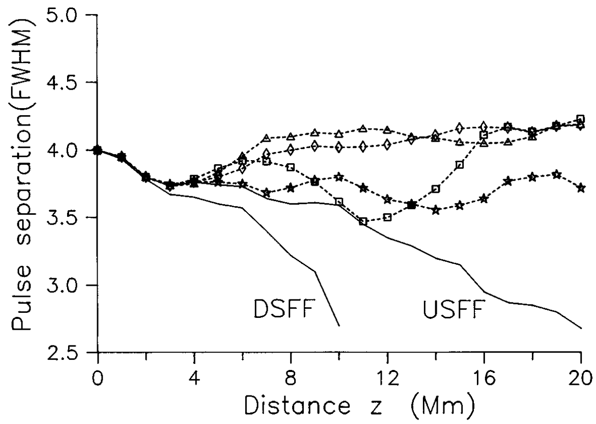

Fig. 5. Pulse separations along the fiber transmission line with a sliding rate of ±3 GHz and a zigzag period of 9 (□), 12 (△), 14 (◇), and 17 (☆) Mm. The pulse separations with the USFF and the DSFF at a sliding rate of 3 GHz/Mm are also shown for comparison.

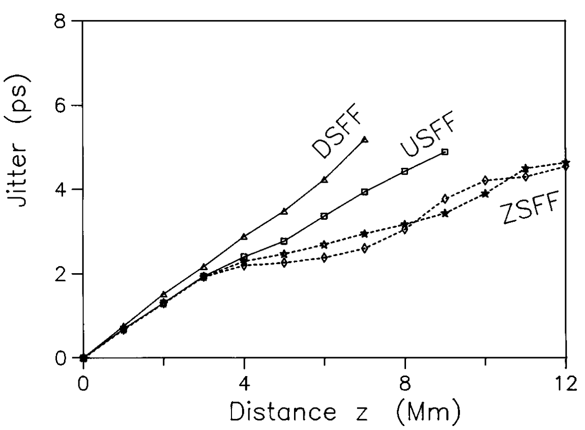

Fig. 6. Evolutions of the standard deviation of the timing jitter of the solitons with different SFF's. For the ZSFF we show two cases with zigzag periods of 12 (◇) and 14 (☆) Mm.

zigzag periods are 6, 8, 9, and 11 Mm. The pulse separations with the USFF and the DSFF are also shown for comparison. It can be seen that the pulse separations are maintained well where the zigzag periods are 8 and 9 Mm. In Fig. 5 we show the pulse separations along the transmission distance with the ZSFF at the sliding rate ±3 GHz/Mm in which the zigzag periods are 9, 12, 14, and 17 Mm; the pulse separations are maintained well for zigzag periods of 12 and 14 Mm. From Figs. 4 and 5 we can see that the ZSFF effect is not good when the maximum of center frequency of the sliding filter is too small or too large. From the numerical calculations we find that the optimum sliding rate lies in the 2–4-GHz/Mm region, and the optimum zigzag period is such that the maximum center frequency of the sliding filter is approximately half of the bandwidth of the soliton pulse.

In the real system, there is the noise introduced by the optical amplifiers. The noise randomly modulates the soliton carrier frequency and causes the timing jitter of the system. The combined effect of the soliton interaction and the timing jitter that is due to the noise is complicated. Considering the system with a 20-ps pulse width and a 4-pulse-width separation (12.5 Gbits/s), a 10^{-9} bit error rate corresponds to a 4.7-ps standard deviation of the timing jitter. With the sliding rate of 3 GHz/Mm and a zigzag period of 12 and 14 Mm for ZSFF, Fig. 6 shows the evolutions of the standard deviation along the fiber with different SFF's where the spontaneous emission factor of an amplifier is assumed to be 1.2. We calculate the standard deviation by simulating the transmissions of 512 pseudorandom bits. From Fig. 6 the allowed transmission distances for a 10^{-9} bit error rate are 6.5, 8.4, and 12 Mm. With a sliding rate of 4 GHz/Mm and a zigzag period of 8 Mm for the ZSFF, we also calculate the standard deviation along the fiber with different SFF's: the allowed transmission distances for a 10^{-9} bit error rate are 5.4, 6.8, and 11 Mm for the DSFF, USFF, and ZSFF, respectively. As the accumulated noise powers are approximately the same with the three different filters, the improvement of the transmission distance with the ZSFF is due mainly to the reduction of the soliton interaction.

In conclusion, the reductions of soliton interaction by the DSFF, the USFF, and the ZSFF are numerically studied. It is shown that the upsliding case is better than the downsliding case because the soliton pulse width for the case with the USFF is less than that of the case with the DSFF as a result of the dispersion changed by the filters. On the other hand, the ZSFF alternately changes the sign of the relative frequency of the two solitons transmitting along the fiber and stabilizes the soliton separation. Therefore the soliton interaction can be significantly reduced with the ZSFF.

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References

1. Y. Kodama and S. Wabnitz, Electron. Lett. **27,** 1931 (1991).
2. A. Mecozzi, J. D. Moores, H. A. Haus, and Y. Lai, Opt. Lett. **16,** 1841 (1991).
3. Y. Kodama and S. Wabnitz, Opt. Lett. **18,** 1311 (1993).
4. L. F. Mollenauer, J. P. Gordon, and S. G. Evangelides, Opt. Lett. **17,** 1575 (1992).