Reversing intrachannel ghost-pulse generation by midspan self-phase modulation

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Intrachannel pulse interactions are the dominating nonlinear effects in modern transmission systems with high modulation speeds. Scaled symmetries have proved to be effective in suppressing amplitude and timing jitter of mark pulses due to nonlinearity but not for ghost-pulse generation into the empty slots. A method of using midspan self-phase modulation to reverse the generation of ghost pulses due to intrachannel four-wave mixing is proposed. Computer simulations demonstrate significant improvement of signal quality by a combination of scaled symmetries and midspan self-phase modulation.

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In high-speed long-distance fiber-optic transmissions, a major limitation is imposed by intrachannel nonlinear effects such as pulse amplitude and timing jitter due to intrachannel cross-phase modulation (IXPM) and intrachannel four-wave mixing (IFWM), respectively.[1] A method has been proposed to suppress intrachannel nonlinearities by use of Raman-pumped transmission lines manifesting a lossless or mirror-symmetric map of signal power.[2,3] However, the loss of pump power makes it difficult to maintain a constant gain in a long transmission fiber. Consequently, the significant deviation of signal power profile from a desired mirror-symmetric map degrades the result of intrachannel nonlinear compensation using mirror symmetry.[4] Recently, it has been shown that transmission lines designed with translation symmetries in power and dispersion maps could also effectively compensate for IXPM and one aspect of IFWM, greatly reducing timing and amplitude jitter.[5,6] In particular, the mathematical formulation in Ref. 6 provides a general and unified theory of intrachannel nonlinearity compensation using translation or mirror symmetry, and, more importantly, it emphasizes the necessity of scaling the dispersion and the loss coefficient, as well as the product of the nonlinear coefficient and the signal power in fibers, for optimal nonlinearity compensation. One aspect of IFWM is amplitude fluctuation in the pulse-ON slots as a result of coherent superpositions of nonlinearly generated fields onto the original pulses. However, neither the mirror nor the translation symmetry can hold back another aspect of IFWM, namely, the generation of ghost pulses into the pulse-OFF slots, where originally there are no optical pulses.[7–10] The growth of ghost pulses will eventually limit the transmission distance. Here we show that self-phase modulation (SPM) in the middle can make the two parts of a long transmission line generate ghost amplitudes of opposite sign, such that the ghost pulses are annihilated or greatly suppressed at the end.

The amplitude envelope of a single channel may be represented by a sum of optical pulses, $A(z,t) = \Sigma_k u_k(z,t)$, where $u_k(z,t)$ denotes the pulse in the kth time slot, centered at time $t=kT$, with $k \in \mathbf{Z}$ and $T > 0$ being the duration of one symbol. The following nonlinear Schrödinger equation describes the propagation and nonlinear interactions among the pulses[1,6]:

$$\frac{\partial u_k}{\partial z} + \frac{i\beta_2(z)}{2}\frac{\partial^2 u_k}{\partial t^2} + \frac{\alpha(z)}{2}u_k = i\gamma(z)\sum_m \sum_n u_m u_n u^*_{m+n-k}, \quad \forall\, k \in \mathbf{Z}, \tag{1}$$

where the right-hand side keeps only those nonlinear products that satisfy the phase-matching condition. The nonlinear mixing terms with either $m=k$ or $n=k$ contribute to SPM and IXPM, while the rest with both $m \neq k$ and $n \neq k$ are responsible for IFWM.[1,6] For a pulse-OFF time slot, for example, the kth, the original pulse amplitude $u_k(0,t)=0$, however, the Kerr nonlinearity will generate a ghost amplitude into this slot. In the regime of weak nonlinearity where perturbation theory[6] applies, the ghost amplitude is approximated by a linear accumulation of nonlinear products over the propagation distance,

$$u_k(z,t) \approx \int_0^z i\gamma(s) \sum_{m\neq k} \sum_{n \neq k} u_m(s,t) u_n(s,t) u^*_{m+n-k}(s,t)\mathrm{d}s. \tag{2}$$

Consider two transmission lines in cascade, one stretching from $z=0$ to $z=L$, the other from $z=L$ to $z=L+L'$. Assume dispersion is compensated for in each line such that optical pulses return approximately to their original shapes at $z=L$ and $z=L+L'$. Each line may consist of multiple power-repeated and dispersion-equalized fiber spans that are suitably arranged to form a scaled translation or mirror symmetry. Therefore, both lines are effective for suppressing the timing and amplitude jitter in the pulse-ON slots. However, they are not able to prevent the growth of ghost amplitudes in the pulse-OFF slots. The two lines are not necessarily the same but are assumed to generate approximately the same ghost amplitudes,

$$\int_{L}^{L+L'} i\gamma(z) \sum_{m\neq k} \sum_{n\neq k} u_m(z,t)u_n(z,t)u^*_{m+n-k}(z,t)\mathrm{d}z \approx u_k(L,t) = \int_{0}^{L} i\gamma(z) \sum_{m\neq k} \sum_{n\neq k} u_m(z,t)u_n(z,t)u^*_{m+n-k}(z,t)\mathrm{d}z, \tag{3}$$

for all pulse-OFF slots labeled with k. So the ghost amplitude will accumulate into $u_k(L+L',t) = 2u_k(L,t)$ at the end, as long as the perturbation assumption holds. If the transmission lines become too long, the approximation of linear accumulation of ghost amplitudes will eventually break down. The ghost amplitudes will actually grow exponentially as a result of parametric amplification pumped by the mark pulses. A method of ghost-pulse suppression may be needed to clean the ghost amplitudes or to reverse their accumulation before they become too strong.

Now consider introducing a self-phase modulator for each wavelength channel in the middle of the two lines at $z=L$ and adjusting the signal power such that the amount of nonlinear phase shift reaches approximately π at the peak of an optical pulse. After such mid-span SPM, all originally ON pulses acquire approximately a π phase shift, while the ghost pulses in the originally OFF time slots experience small to negligible phase shifts due to their low power level. As a consequence, the IFWM products generated in the second line from $z=L$ to $z=L+L'$ would acquire a factor of $(-1)^3=-1$ compared with when midspan SPM is absent. Instead of adding constructively, the ghost amplitudes generated by the two lines interfere destructively to cancel each other at the end $z=L+L'$. Good transmission performance may be expected from the overall system as a result of the suppression of amplitude and timing jitter for originally ON pulses and the elimination of ghost pulses in the originally OFF time slots.

For implementations, the self-phase modulator may be based on fiber Kerr nonlinearity,[11] cascaded $\chi^{(2)}$ in $LiNbO_3$ waveguides,[12,13] index change induced by carrier density variations in semiconductor optical amplifiers,[14] or a combination of a photodiode detecting the optical pulses and an electro-optic phase modulator driven by the generated electrical pulses.[15,16] A fiber-based self-phase modulator may be a better choice than other modulators because of its simplicity and capability of polarization-insensitive operation. Furthermore, a suitable value of fiber dispersion may be chosen such that optical pulses propagate in a solitonlike manner through the nonlinear fiber, to reduce pulse spectral broadening due to SPM.[11] If SPM is not properly balanced by dispersion, then only the peak of a pulse receives a π phase shift, and the rising and falling edges experience smaller and varying phase shifts, which leads to frequency chirp and spectral broadening. Excessive spectral broadening may cause cross talk among wavelength channels and decrease the spectral efficiency (rate of data transmission in bits/s over the available optical bandwidth in Hz) of transmission systems. A soliton, namely, a hyperbolic secant pulse, could propagate invariantly in a lossless fiber given the condition $-\beta_2=\gamma P_0 T_0^2$, where β_2 and γ are the dispersion and nonlinear coefficients of the fiber, respectively, and P_0 and T_0 are the peak power and width parameter of the pulse, respectively.[11] For actual fibers with loss, strict soliton propagation may not be possible, but the total fiber dispersion may be adjusted to minimize the frequency chirp of pulses at the end or to control the chirp at a desired level. An optical filter may also be employed after SPM to limit the spectral width of pulses.

For numerical verifications, we have simulated and compared the performance of three transmission lines, all of which use standard single-mode fibers (SMFs) with loss $\alpha=0.2$ dB/km, dispersion $D=16$ (ps/nm)/km, effective modal area $A_{\mathrm{eff}}=80\ \mu\mathrm{m}^2$, and reverse dispersion fibers (RDFs) with loss $\alpha'=0.2$ dB/km, dispersion $D'=-16$ ps/nm/km, effective modal area $A'_{\mathrm{eff}}=30\ \mu\mathrm{m}^2$, and erbium-doped fiber amplifiers (EDFAs) with a noise figure of 4 dB. The first setup is a conventional design consisting of 16 fiber spans in which each span has a 45 km SMF, followed by a 45 km RDF and an 18 dB EDFA at the end. The second setup is configured to form a scaled translation symmetry,[6] with eight repetitions of (50 km SMF + 50 km RDF + 16 dB EDFA) + (40 km RDF + 40 km SMF + 20 dB EDFA). Note that the EDFA gains are set such that the signal powers into the 50 km SMF and the 40 km RDF are properly scaled.[6] The third system is the same as the second, except for channelized SPM in the middle, due to the use of a high-power EDFA, an optical demultiplexer–multiplexer (DEMUX/MUX) pair, and for each channel a 10 km nonlinear fiber with effective modal area $A''_{\mathrm{eff}}=20\ \mu\mathrm{m}^2$, loss $\alpha''=0.3$ dB/km, and dispersion $D''\approx 3$ ps/nm/km. The peak power of pulses is boosted to 80 mW at the input to each SPM fiber and attenuated back to the nominal level for transmissions after the self-phase modulator. All fibers are made from silica glass with nonlinear index $n_2=2.6\times 10^{-20}\ \mathrm{m}^2/\mathrm{W}$. Input to all three systems is four 40 Gbits/s channels, spaced by 200 GHz, copolarized, and return-to-zero modulated with 33% duty and peak power of 15 mW. The optical filters are of order 7 with a bandwidth of 100 GHz for MUX/DEMUX. The transmission results are shown in Fig. 1. It is evident that the conventional setup suffers a great deal from nonlinearity-induced amplitude and timing jitter, which is greatly reduced in the system with scaled translation symmetry, where, however, ghost-

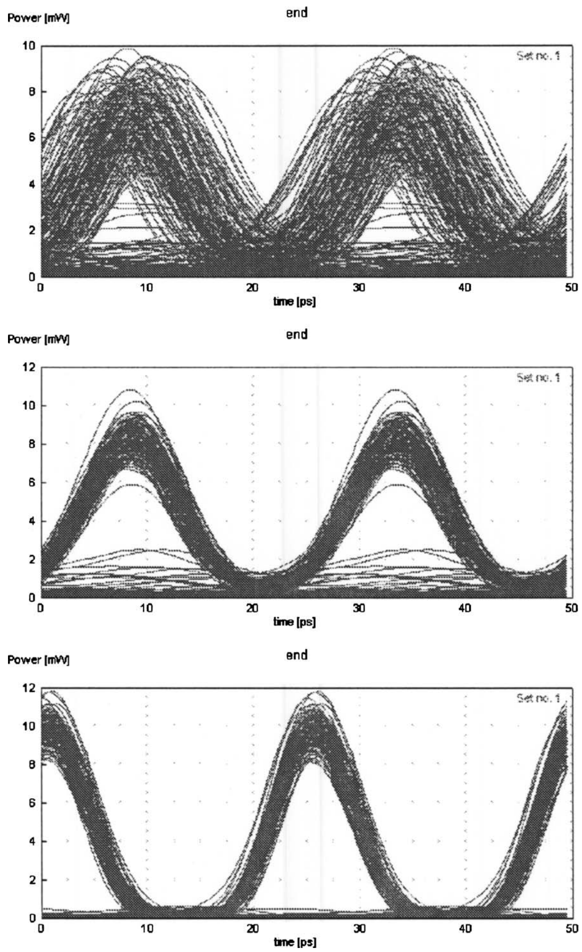

Fig. 1. Optical eye diagrams at the end of transmissions: top, conventional design without translation symmetry; middle, system with a scaled translation symmetry; bottom, system with scaled translation symmetry and midspan SPM.

pulse generation imposes a serious limitation. With both scaled translation symmetry and midspan SPM, the third system enjoys superb signal quality at the end, with small signal fluctuations due to EDFA noise and possibly a little residual nonlinearity.

It is interesting to compare the present method of midspan SPM and signal reshaping based on nonlinear optical loop mirrors (NOLMs),[17,18] both of which are able to suppress ghost pulses and are channelized solutions that are suitable for systems with a high modulation speed, because there are fewer wavelength channels and higher optical power is available in each channel for efficient nonlinear effects. While a NOLM is often regarded as a lumped signal regenerator, midspan SPM may be viewed as a method of distributive signal regeneration, whose action takes place through an entire transmission line. Practically, midspan SPM would be more convenient than using NOLMs, as the latter require interferometry stability and are sensitive to variations of fiber birefringence.[19] On the other hand, NOLMs are capable of removing random optical noise due to amplified spontaneous emission and loss-induced quantum noise,[20] while midspan SPM is not.

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