Feature of Optical Soliton Sequence Propagation in Single-Mode Fiber

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Abstract. Estimates of information capacity of the optical system as product of maximum data rate in single soliton channel and long span distance are considered. The linear (fiber group velocity dispersion and optical losses) and nonlinear (self-phase modulation and Raman self-frequency shift) effects, the signal/noise ratio of pulse source are included in pulse evolution description. It was shown, that maximum optical system capacity can be achieved with NZDS-fiber.

1. Introduction

One important parameter of the fiber optic data system is the information capacity defined as the product of the bit rate $B$ by the transmission distance $z$ (the length of the span). Information capacity of a data transmission system directly depends on symbol pulse width $T_o$ and their peak power $P$. Increase in speed of data transmission assumes reduction of duration of symbol pulse: the bit rate $B = (Q^* T_o)^{-1}$, where $Q$ is on-off time ratio, that leads to broadening of a spectrum of symbol pulse that accelerates dispersive broadening of symbol pulse, on the one hand, and at the high power causes manifestation of nonlinear effects in the fiber light guide with another. To achieve bit rate 10 Gbit/s and more the symbol pulses of the picosecond and subpicosecond width must be used. Optical pulses of the subpicosecond width experience a strong dispersion broadening when propagated over the fiber-optics link. The dispersion compensation fibers (DCF) must be used at the end of the link to compensate accumulated dispersion. But DCF usually makes a big optical loss. To compensate the optical loss can be used optical amplifiers. But optical amplifiers make additional noise, so the signal-noise ratio gets worse. Therefore, dispersion compensation methods at the physical level are of interest for the high bit rate long haul fiber-optics systems. Such nonlinear effects as the self-phase modulation can be used to compensate the optical symbol pulse dispersion broadening.

Nonlinear effects of different nature have different effects on momentum evolution [1-14]. The self-phase modulation can be used to compensate for the dispersion expansion of the pulse in the region of abnormal dispersion. However, other nonlinear effects may have a negative effect on bit pulse dynamics. Thus, at the subpicosecond width of the symbol pulse, Raman self-scattering can have a significant influence on its evolution. The features of propagation of optical pulses of subpicosecond width in the fiber considering both linear (fiber dispersion and optical losses) and nonlinear (self-phase modulation, Raman self-frequency shift) effects, as well as influence of noise of the source of these pulses are considered. It is shown that it is possible to optimize the parameters of the fiber-optics communication system in order to increase its information capacity.
2. The features of propagation of optical soliton of subpicosecond width

The solitons can be used as the symbol pulses in bit stream in order to overcome the dispersion limitation. The initial balance between the dispersion and nonlinearity represents the fundamental optical soliton when the initial power $P_o$ of the solitons:

$$P_o = \frac{\beta_2}{(\gamma \tau_o^2)}$$

where $\beta_2$ – is the fiber dispersion $d^2 \beta / d \omega^2$, $\beta$ – is the propagation constant, $\omega = 2 \pi f$ is the frequency, $\gamma$ - nonlinear Kerr coefficient, $\tau_o = T_o / 1.763$. The initial soliton energy $E_o = 2P_o \tau_o$. For SSMF (Standard Single Mode Fiber) $\beta_2 = 18 \text{ ps}^2/\text{km}$, and $\beta_2 = 2 \text{ ps}^2/\text{km}$ for NZDS (Non-Zero Dispersion Shifted Fiber) fiber can be used. In a real fiber there is some small loss.

When fiber loss is included, the total energy $E(z)$ in a pulse decay with the distance along the fiber and is proportional to $\exp(-2\alpha z)$. $z$ – distance, $\alpha$ - fiber loss. If we assume a level loss in SSMF of 0.2 dB/km, $\alpha = 0.023 \text{ km}^{-1}$. If the loss length $\alpha^{-1}$ is long compared to the dispersion length $L_D$: $L_D = \tau^2 / \beta_2$, the pulse width changes as $\Delta(\tau(z) = \tau_o \exp(2\alpha z)$.

The self-frequency shift of a soliton is extremely sensitive to the pulse width [8, 9]:

$$\Delta \omega_R(z) = \frac{8}{15} \frac{\beta_2 |g(\tau_o) T_R z}{\tau^2}$$

$T_R$ – is the Raman parameter, typically $T_R = 3 \text{ fs}$ for the optical fiber [3], $g(\tau_o)$ – weak function of $\tau_o$.

For optical pulses of subpicosecond width: $g(\tau_o) \sim 1$.

The change in position of the center $t_R$ from its original value

$$t_R = \frac{1}{15} \frac{\beta_2^2 T_R g(\tau_o)}{\tau_o^2} \alpha \left( z - \frac{1 - \exp(-8\alpha z)}{8\alpha} \right)$$

This frequency shift in center of each pulse in a bit stream would not cause problem to data carrying capacity. But if the initial pulse width fluctuates as result of laser noise an error can occur at the end of fiber-optics communication system. The self-frequency shift result to the change in position of the center $t_R$ from its original value. In practical the fluctuations in the solitons pulse width $\Delta T$ can be induced by changes in the energy $\Delta E$ from the laser as well as noise in the input pulse: $\Delta E/E = \Delta T/T$.

The change in the output pulse position $\Delta t_R$ is obtained:

$$\Delta t_R = \frac{4}{15} \frac{\beta_2^2 T_R \Delta \tau_o^2 g(\tau_o)}{\tau_o^2} \alpha \left( z - \frac{1 - \exp(-8\alpha z)}{8\alpha} \right)$$

Let us determine the admissible value of $\Delta t_R$ less than half the clock interval: $\Delta t_R < 2/B$, where $B$ is the bit rate. For soliton systems, $Q = 10$ is usually taken. Then the permissible range of information transfer $z$ can be estimated from (1), for the case when the input fluctuations $\Delta T_o/T_o = 0.001$ (signal/noise ratio of the symbol pulses source $10^3$). With an increase in the initial width $T_o$, the self-scattering effect weakens and the permissible range $z$ increases (Figure 1). However, the length of the soliton propagation regime also depends on $T_o$. 


3. Results

The information capacity defined as the product of the bit rate $B$ by the transmission distance $z$ for soliton system is presented in Figure 2. When using NZDS fibers with a symbol pulse width $T_o$ nearly 1 ps, the maximum information capacity 15 TBit/s $\bullet$ km is achieved.

4. Conclusion

It is shown that for fiber with predetermined parameters, it is possible to determine a range of initial symbol pulse durations $T_o$ at which it is possible to realize a maximum range $z$ at a high bit pulse rate $B$ such that the time jitter caused source amplitude fluctuation will be small.
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