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OPTIMAL LENGTH OF LIGHT PULSES IN NONLINEAR OPTICAL FIBRE CHANNELS

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Abstract—The maximum rate of signal transmission through nonlinear optical fibres has been obtained as a function of fibre length and signal parameters by numerically solving a nonlinear Schrödinger equation describing the evolution of the envelope of intense short pulses in the waveguide. The optimal pulse durations have been determined as functions of the coefficient of nonlinearity, transmission length, and shape and power of pulse signals. The behaviour of soliton-like pulses and Gaussian pulse shapes has been compared from the standpoint of transmission capacity in nonlinear optical fibre communication channels.

Progress in optical fibre technology and the development of single-mode low-loss lightguides now permit data transmission rates as high as several gigabits per second. In digital communication systems, a major factor limiting the further improvement of transmission rates in optical fibres (much as in most other communication channels) is the dispersive spreading of pulse signals, and this increases sharply in significance for ultrashort pulses. Therefore, the recently devised method of compensation of dispersive deformations with the aid of the nonlinear phenomena arising in the transmission of pulses of high intensity [1–3] has inspired general interest. According to the preliminary estimates of Hasegawa and Kodama [2] the use of solitons, stationary pulses formed with complete mutual compensation of the dispersive and nonlinear deformations under negligibly small losses, can increase the transmission rate by one or two orders of magnitude over that of the best linear communication systems. Considerable attention has also been attracted by the topic of nonstationary evolution modes [3].

Estimates of transmission rate are usually deficient unless they make allowance for the nonlinear interaction of adjacent pulses in a message train. Indeed, the average transmission rate is often taken as the inverse of the minimum length of a single pulse. It is quite obvious, however, that pulse to pulse interaction should be taken into account. In order to reduce this error Shiojiri and Fujii [4] in particular, have suggested shifting the phases of adjacent pulses by π; however this is a hard technical task for pulses of several picosecond length.

In this paper we investigate the dependence of the attainable transmission rate on the length of pulses which propagate in a nonlinear optical fibre channel.

To describe the evolution of high-power ultrashort pulses propagating in a fibre waveguide we adopt a model, as is common for such problems [1–3], in the form of the nonlinear Schrödinger equation

$$\mathrm{i}\frac{\partial\psi}{\partial\eta}+\frac{\partial^2\psi}{\partial\tau^2}+\chi|\psi|^2\psi=0 \tag{1}$$

where η, τ are dimensionless variables related to the longitudinal coordinate z and real time t through the characteristic dimensions L_0 and T_0 (dispersion length and initial pulse halfwidth, for example) and the group velocity v_0 by

$$\eta = z/L_0, \qquad \tau=\frac{t-z/v_0}{T_0};$$

$\psi(\eta, \tau)$ is the complex envelope of the optical signal normalized to the initial amplitude; and χ is the nonlinearity parameter defined by the characteristics of the fibre and the initial power of the pulse.

Equation (1) does not take account of losses in the waveguide, dependence of the group velocity on intensity, higher orders of dispersion, and some other phenomena whose effect on the pulse interaction is a subject of a separate study.

Equation (1) was solved numerically under the initial condition

$$\psi(0,\tau)=\psi_0(\tau)=f(\tau-\Delta\tau)+f(\tau+\Delta\tau) \tag{2}$$

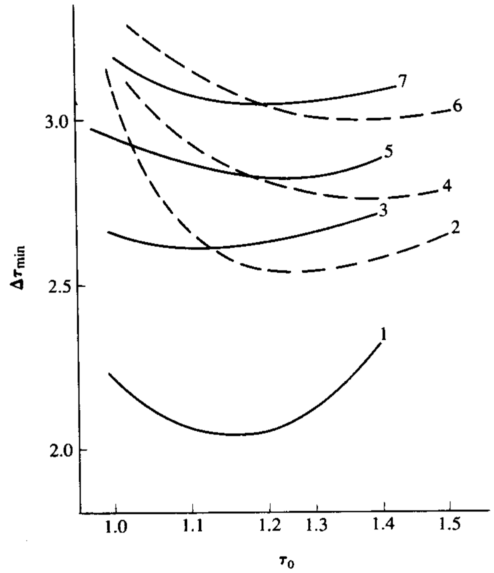

Fig. 1. Minimum pulse spacing for various pulse shapes (soliton-like pulses—continuous line; Gaussian pulses—broken line) versus the initial pulse duration for different transmission lengths: (1) $z = 2L_0$, (2, 3) $z = 4L_0$, (4, 5) $z = 6L_0$ and (6,7) $z = 8L_0$.

where $f(\tau)$ is the pulse at the input of the fibre, and $\Delta\tau$ is the half-spacing between the adjacent pulses. We considered two pulse shapes, the one corresponding to solitons

$$f(\tau) = \text{sech}\left(\sqrt{\frac{\chi}{2}}\frac{\tau}{\tau_s}\right)$$

and a Gaussian shape

$$f(\tau) = \exp(-\tau^2/2\tau_g^2),$$

where τ_s and τ_g are the parameters of equivalent pulsewidth. To make the results of evolution comparable, these parameters were selected such that the pulsewidth measured at the level of half maximum intensity was identical for both shapes. This was achieved at

$$\tau_g = \sqrt{\frac{2}{\chi}}\frac{\text{arcosh}^{-1}\sqrt{2}}{\ln 2}\tau_s.$$

Whether or not two overlapping pulses can be resolved depends to a certain extent on the characteristics of the receiver. We deemed two overlapping pulses to be resolvable provided the intensity at the midpoint between their centres is below one half of their peak intensity.

The numerical solution of Eq. (1) subject to the initial condition (2) and various values of $\Delta\tau$ and τ_s related the maximum distance of transmission η_r, at which the pulses can still be resolved in the above sense, with the halfspacing $\Delta\tau$. Figure 1 shows the minimum admissible halfspacing $\Delta\tau_{min}$ (at the fibre input) as a function of pulsewidth τ_s for different values of the normalized distance of transmission η_r and $\chi = 2$. The plots were constructed as a result of the study. With reference to these curves it is an easy matter to estimate for each particular situation the maximum attainable modulation rate

$$V_{max} = \frac{1}{T_0\Delta\tau_{min}} \quad [s^{-1}],$$

which in binary coding coincides with the maximum transmission rate in bits/s.

Analysis of the results of the simulation indicates that in some cases the nonlinear interaction of pulses can markedly impair their resolvability as compared with simple linear overlapping. Therefore one should be cautious in using estimates of ultimate transmission rate derived without consideration of this factor.

As can be seen from the curves, to each combination of parameter values there corresponds a certain optimal value of the initial pulsewidth that allows for the highest transmission rate. This is natural, for the resolvability of shorter pulses improves at the initial stage of evolution, whereas the dispersion increases and mars the resolution at longer distances.

The quasi-periodic behaviour typical of nonlinear evolution modes leads to a nonmonotonic dependance of these optimal values upon transmission distance.

Comparison of the results for different pulse shapes indicates that for small initial pulsewidths τ_s (about unity) the soliton pulses allow higher transmission rates than their Gaussian counterparts of the same width and power. However, the maximum transmission rates corresponding to the optimal values of τ_s proved to be higher for the Gaussian shapes.

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