Optica Applicata, Vol. XXIV, No. 4, 1994

Propagation of subpicosecond soliton-like pulses in optical fibres

D. MIHALACHE, D. MAZILU, N.-C. PANOIU

Institute of Atomic Physics, Department of Theoretical Physics, P.O. Box MG-6, Bucharest, Romania.

F. MOLDOVEANU

University of Maryland, College Park, Department of Physics, Maryland 20742, USA.

D.-M. BABOIU

CREOL, University of Central Florida, Orlando, Florida 32826, USA.

We investigated the possibility of propagation under the influence of the Raman effect of certain subpicosecond soliton-like pulses which are solutions of a perturbed nonlinear Schrödinger equation describing the propagation of light waves in monomode optical fibres. We calculated the propagation distance limits of long-haul transmission systems caused by the intrapulse Raman scattering soliton timing jitter and the amplified spontaneous emission noise induced timing jitter.

In long-distance soliton transmission systems, subpicosecond pulses are required for bit rates higher than 100 Gbit/s. The major difficulty that impedes on stable subpicosecond pulse propagation in fibres is the presence of the soliton self-frequency shift caused by the intrapulse Raman scattering (IRS) effect [1]. The IRS effect causes a downshift of the mean frequency of the pulse and thus moves it outside the minimum loss window. Although this deleterious effect can be partially overcome with the use of the adiabatic soliton trapping in an active transmission line with a finite optical-gain bandwidth, subpicosecond solitons were successfully transmitted only over a few tens of kilometers [2].

When soliton-like pulses are used as natural bits of information in ultralong communication systems, transmission distance limitations are imposed by the presence of random timing jitter caused by the Gordon–Haus effect [3] and the IRS effect [4]. Recently, by using sliding-guiding filters, a substantial reduction of the Gordon–Haus jitter, which is the main limitation of the information capacity of long-distance picosecond soliton transmission systems, was reported [5].

The model equation [6] for the complex pulse envelope amplitude of the light wave in monomode optical fibres in the subpicosecond-femtosecond domain is:

$$i\frac{\partial q}{\partial Z}+\frac{1}{2}\frac{\partial^2 q}{\partial T^2}+i\varepsilon\frac{\partial^3 q}{\partial T^3} = -N^2\left[|q|^2 q+i\alpha_1|q|^2\frac{\partial q}{\partial T}+(i\alpha_2-\tau_R)q\frac{\partial}{\partial T}(|q|^2)\right] \tag{1}$$

where:

$$Z=\frac{|\beta_2|z}{T_0^2},\quad T=\frac{t-z/v_g}{T_0},\quad N^2=\frac{n_2\omega_0 P_0 T_0^2}{cA_{\rm eff}|\beta_2|},$$
$$\varepsilon=\frac{-\beta_3}{6|\beta_2|T_0},\quad \alpha_1=\frac{2}{\omega_0 T_0}+\frac{n'}{nT_0}+\frac{2r'}{rT_0},\quad \alpha_2=\frac{2}{\omega_0 T_0}+\frac{n'}{nT_0}+\frac{4r'}{rT_0},\quad \tau_R=\frac{T_R}{T_0}. \tag{2}$$

In Equation (2), β_2 is the group-velocity dispersion coefficient, β_3 is the third-order dispersion coefficient, v_g is the group velocity, T_0 is the pulse width ($T_{\rm FWHM}=1.763\ T_0$), n is the linear index of refraction, n_2 is the Kerr nonlinearity coefficient, ω_0 is the carrier frequency, c is the velocity of light, $A_{\rm eff}$ is the effective core area, P_0 is the peak power of the input pulse, r is the frequency-dependent radius of the fibre mode [7], and T_R is related to the slope of the Raman gain ($T_R\simeq$ 6 fs). Primes denote the derivative with respect to frequency, and all parameters are evaluated at carrier frequency ω_0. Equation (1) does not take into account the fibre loss because it is assumed to be overall compensated by the technique of distributed amplification.

We notice that the soliton-like solutions [8] of Equation (1) are not true solitons for every ratio of the parameters ε, α_1 and α_2 but for $\varepsilon:\alpha_1:\alpha_2=1:6:0$ (Hirota equation [9]) and for $\varepsilon:\alpha_1:\alpha_2=1:6:3$ (Sasa-Satsuma equation [10], [11]).

We see from relations (2) that the coefficients of higher order nonlinear terms are approximately equal $\alpha_1\simeq\alpha_2$. If the ratios of the parameters ε, α_1 and α_2 are $1:2:2$, the soliton-like solution of Eq. (1) for soliton number $N=1$ will not exhibit any frequency shift and it has the simple form

$$q(T,Z)=\eta\,\mathrm{sech}[\eta(T-v^{-1}Z-T_0)]\exp(i\varkappa Z+i\varphi_0) \tag{3}$$

where: $v^{-1}=\varepsilon\eta^2$, $\varkappa=\frac{1}{2}\eta^2$.

The ratio $1:2:2$ can be achieved, for example, for the following two sets of the fibre parameters: $\beta_2=-2.5$ ps^2/km, $\beta_3=-0.012$ ps^3/km or $\beta_2=-0.5$ ps^2/km, $\beta_3=-0.0025$ ps^3/km at $\lambda=1.55$ μm.

Following the same procedure as in [3], one can obtain for a 10^{-9} error rate the following upper limit on the system length–bit rate product due to the ASE noise random timing jitter: $L^3R^5=3.857\times10^{22}$ km^3 GHz^5, where L is the overall length of the system, and R is the bit rate. The following set of parameter values: $A_{\rm eff}=$ 25 μm^2, $\Gamma=0.0461$ km^{-1}, $n_2=3.18\times10^{-16}$ cm^2/W, $\beta_2=-0.5$ ps^2/km, $\beta_3=-0.0025$ ps^3/km, $\lambda=1.55$ μm, $|D|=0.4$ ps (nm·km), $T_{\rm FWHM}R=0.1$, $t_wR=$ 1/3 ($2t_w$ is the window of detector acceptance for a soliton), yields the maximum distance $L=10810$ km for a bit rate $R=125$ Gbit/s. We notice that in the case of picosecond solitons, for the above fibre parameters, the Gordon–Haus formula for the transmission system length–bit rate product gives the following result: $L^3R^3=9.86\times10^{13}$ km^3 GHz^3. This formula holds to the maximum distance $L=4620$ km for a bit rate $R=10$ Gbit/s.

In order to study the IRS soliton timing jitter, one has to evaluate first the self-frequency shift for the solitary wave (3). Thus, for $\varepsilon:\alpha_1:\alpha_2=1:2:2$, by propagating the input pulse $q(T, 0) = \eta \operatorname{sech} \eta T$ in the presence of the Raman term over 1200 dimensionless units (corresponding to a distance $L = 500$ km for a fibre with $|D| = 0.4$ ps/(nm·km)) we obtained by numerical simulations the following self-frequency shift:

$$\frac{d\nu_0}{dz}\left[\frac{\mathrm{THz}}{\mathrm{km}}\right] = 0.0051\ \frac{\beta_2[\mathrm{ps}^2/\mathrm{km}]}{T^4_{\mathrm{FWHM}}[\mathrm{ps}^4]} \tag{4}$$

where ν_0 is the mean soliton frequency and z is the distance along the fibre. It is easy to show that for a soliton with $T_{\mathrm{FWHM}} = 800$ fs and for relative energy fluctuation $|\Delta E|/E = 10^{-2}$, the pulse centre fluctuates by $0.8 \times 10/3$ ps after a distance of 85 km.

References

[1] MITSCHKE F. M., MOLLENAUER L. F., Opt. Lett. **11** (1986), 659; GORDON J. P., *ibid.* **11** (1986), 662.

[2] BLOW K. J., DORAN N. J., WOOD D., J. Opt. Soc. Am. B **5** (1988), 1301; NAKAZAWA M., KUROKAWA K., KUBOTA H., YAMADA E., Phys. Rev. Lett. **65** (1990), 1881; NAKAZAWA M., KUBOTA H., KUROKAWA K., YAMADA E., J. Opt. Soc. Am. B **8** (1991), 1811.

[3] GORDON J. P., HAUS H. A., Opt. Lett. **11** (1986), 665.

[4] WOOD D., J. Lightwave Technol. **8** (1990), 1097.

[5] MOLLENAUER L. F., MAMYSHEV P. V., NEUBELT M. J., Opt. Lett. **19** (1994), 704.

[6] KODAMA Y., HASEGAWA A., IEEE J. Quantum Electron. **23** (1987), 510.

[7] SINGER F., POTASEK M. J., FANG J. M., TEICH M. C., Phys. Rev. A **46** (1992), 4192.

[8] POTASEK M. J., TABOR M., Phys. Lett. A **154** (1991), 449; MIHALACHE D., PANOIU N.-C., TRUTA N., MOLDOVEANU F., Romanian J. Phys. **38** (1993), 213.

[9] HIROTA R., J. Math. Phys. **14** (1973), 805.

[10] SASA N., SATSUMA J., J. Phys. Soc. Jpn. **60** (1991), 409.

[11] MIHALACHE D., TORNER L., MOLDOVEANU F., PANOIU N.-C., TRUTA N., J. Phys. A **26** (1993), L757; Phys. Rev. E **48** (1993), 4699.