Revista Mexicana de Física 37 No. 1(1991) 1-7

Alteration of the soliton behavior in silica-fibers doped with passive resonant atoms

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(Recibido el 22 de mayo de 1990; aceptado el 1 de agosto de 1990)

Abstract. We have numerically studied for the first time the full dynamics describing the pulse propagation phenomenon in single-mode silica-fibers doped with passive resonant two level atoms. For the specific case of a 3-order soliton we show that the inclusion of the resonant nonlinearities destroys the fundamental characteristics of the pulse soliton behavior.

PACS: 42.50 Qg; 42.81.Dp

Optical solitons in single-mode silica-fibers is the subject of intense current research because it could form the basis of the future long-distance telecommunication systems [1]. The optical soliton is a lossless pulse with specific shape and phase and it appears as a result of the balancing between the linear dispersion and the nonlinear intensity-dependent index of refraction of the material of the optical fiber. As was first theoretically showed by Hasegawa [2], the propagation of a light pulse

$$E(r,z,t) = A(z,t)R(r)e^{i(\omega_L t-\beta_0 z)} \tag{1}$$

through a single-mode optical fiber, whose core is characterized by a refractive index $n_1(\omega, I) = n(\omega) + n_2|E|^2$, where n_2 is the silica Kerr coefficient, is described taking into account the slowly varying envelope approximation by the nonlinear Schrödinger equation (NLSE). If ones assumes an input pulse of the form

$$V(t', z' = 0) = N \operatorname{sech}\left(\frac{t}{t_0}\right), \tag{2}$$

then it is possible to parameterize the obtained NLSE to the following dimensionless

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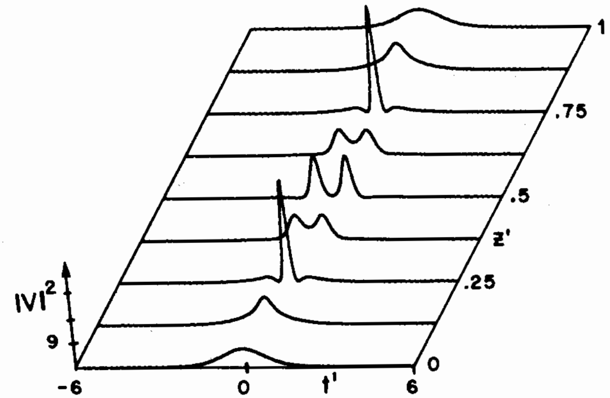

FIGURE 1. Spatial evolution of a third-order soliton solution of Eq. (3) through a repetition period. The input pulse has the form given in Eq. (2) with $N = 3$.

form [3]

$$\frac{\partial V}{\partial z'} = -i\frac{\pi}{4}\frac{\partial^2 V}{\partial t'^2} - i\frac{\pi}{2}|V|^2 V, \tag{3}$$

which is very convenient for computational purposes. In Eqs. (2) and (3),

$$V(z,t) = \frac{A(z,t)}{\sqrt{P_1}} = \tau\left(\frac{n_2\beta_0}{2n_0|\beta_2|}\right)^{1/2} A(z,t),$$

$$z' = \frac{z}{z_0}, \text{ with } z_0 = 0.322\frac{\pi^2 c^2 \tau^2}{\lambda|D(\lambda)|},$$

$$t' = \frac{|t - z/\beta_1|}{t_0}, \text{ with } t_0 = 0.568\tau_0, \tag{4}$$

τ being the pulse width (FWHM), $n_0 = n(\omega_L)$, $\beta_0 = \beta(\omega_L)$, $\beta_1 = \partial\beta/\partial\omega|_{\omega=\omega_L}$, $\beta_2 = \partial^2\beta/\partial\omega^2|_{\omega=\omega_L}$, λ and c are the wavelength and the velocity of light in the vacuum, respectively, and $|D(\lambda)|$ is the group velocity dispersion (GVD) of the fiber in dimensionless units. In the so-called anomalously-dispersive region ($\lambda > 1.3$ μm for silica fibers), β_2 is negative and Eq. (3) accepts soliton solutions, whose modulus follow Eq. (2) with N as an integer [2]. For the fundamental soliton, $N = 1$, which indeed represents a pulse with a peak power P_1, the pulse preserves its initial amplitude and width, while below this threshold, by virtue of the core linear dispersion, the pulse becomes broader and loses amplitude as propagates in the fiber. For input powers above the threshold ($N > 1$, or peak powers greater than P_1) the corresponding solitons follow a shortening and splitting periodic behavior at constant energy, where the original profile is reconstructed each $z = z_0$ distance within the fiber. Figure 1 shows a numerical solution of Eq. (3) for a third-order soliton ($N = 3$), using numerical techniques reported previously [4].

The first experimental observation of the optical soliton predicted by Hasegawa was carried out in 1980 [5]. However, it was evident that nonlinear Kerr effect just compensates the linear dispersion but is unable to suppress the inherent linear fiber loss due to absorption, scattering, etc. Such a linear attenuation enters in the NLSE as an additional term $-\alpha_0 V$ in the RHS of Eq. (3), where α_0 is the loss coefficient, and causes a progressive reduction of the pulse amplitude and an increase in the pulse width [6,7] that eventually ends up in its practical absorption or in the temporal overlapping of a train of pulses sent along the fiber for telecommunicative purposes [8]. Therefore, for long-distance soliton-based telecommunication systems the presence of signal repeaters is needed.

From a practical point of view, optical amplifiers are preferable to opto-electronic ones because they should allow the installation of all-fiber telecommunication systems [9], and several methods for the optical enhancement of the pulse signal have been developed and exhaustively tested in laboratories. For example, solid theoretical studies on the pulse transmission have been carried out by using periodically spaced Ramman-gain based amplifiers [10] and soliton propagation over distances up to 6000 Km have been experimentally demonstrated [11]. Another possibility for fiber optical amplifiers is in the use of rare-earth-doped optical fibers pumped with *cw* lasers and it is currently investigated in laboratories [12]. However, the theoretical exploration of soliton propagation in such fibers are still incomplete and they are limited to studies based on the addition of a gain term ΓV in the RHS of Eq. (3), where the gain coefficient Γ may be merely a constant or also a frequency-dependent function in order to include the spectral limited bandwidth of the saturated doped fiber [13].

As a new possibility for compensating the inherent loss associated with an optical fiber we are now proposing the use of fibers doped with passive resonant atoms in which the cancellation of the linear fiber loss may, in principle, occurs directly by the additional nonlinear interaction between the light pulse and the resonant atoms [14]. If a suitable control on the interaction between the different linear and nonlinear terms should exist in such doped-fiber, then the proposed alternative will be of very practical interest because it will suppress the use of repeaters in soliton-based systems. In this letter we report the first results of the full numerical simulation of the pulse propagation process through a resonant doped fiber. Specifically, we show that an optical soliton which is stable in both systems (the pure fiber and the resonant medium) taken separately, can not be propagated without distortion through the passive-resonant doped-fiber. This particular result, however, does not discard our original idea.

We suppose that the resonant atoms embedded in the core of the single-mode silica-fiber are represented by an ensemble of nondegenerated two level atoms (TLA) [14], possessing a dipole transition d and transition frequencies distributed according to the function $g(\Delta) = g(\omega - \omega_L)$, centered at the pulse carrier frequency ω_L. Therefore, their time evolution in the presence of the electromagnetic pulse is described by the so-called Bloch equations [14]

$$\frac{\partial p}{\partial t'} = i\Delta p + i\gamma V w \tag{5a}$$

$$\frac{\partial w}{\partial t'} = Im(\gamma V p^*), \tag{5b}$$

where p and w are the atomic polarization and the atomic inversion, respectively, while $\gamma = (2d/\hbar)\sqrt{P_1}$. Because the so-called pulse area, $\theta(z')$, defined by the time integral

$$\theta(z') = \frac{2d}{\hbar}\int A(z',t')dt' = \gamma\int V(z',t')dt', \tag{6}$$

mainly determines the pulse behavior in resonant pulse propagation [14], γ is a fundamental parameter giving a quantitative measurement of the relative strength between the Kerr and the resonant nonlinear effects. The influence of the TLA on the pulse is given by the macroscopic resonant polarization envelope [14]

$$P(z',t') = -i\left[\frac{\alpha_0 z_0}{2\pi g(0)}\right]\int p(z',t',\Delta)g(\Delta)\,d\Delta = -iB\langle p\rangle, \tag{7}$$

where α_0 is the on-resonance absorption coefficient. The insertion of the above polarization expression in the RHS of Eq. (3) together with Eqs. (5) form the system of equations governing the pulse propagation through a single-mode resonant-doped optical fiber. It is worth noting that B in Eq. (7) is the other fundamental parameter controlling the relative strength of the resonant nonlinearity because it represents the absorption length in units of the soliton period z_0. Given the dipole transition of the TLA, B can be varied by changing the concentration of resonant atoms in the core of the fiber. For the results presented here, we have set $z_0 = 10\alpha_0^{-1}$ in order to properly appreciate the influence of the TLA on the pulse during one soliton period.

As it was illustrated in Fig. 1, an input pulse of the form given in Eq. (2) with $N = 3$ is a stationary solution of Eq. (3) alone, *i.e.* without considering any additional gain or loss terms. On the other hand, the same input pulse with $\gamma = 0.57$ in Eqs. (5) will represent a 1.7π area pulse for the TLA system alone, *i.e.* without considering the linear and the Kerr dispersion, and therefore, it will evolve to a 2π resonant optical soliton [14]. This last fact is valid for passive TLA, where all the resonant atoms stay in their ground state before the arrival of the pulse. The case of an active resonant medium, when the TLA are initially excited, describes the use of resonant optical amplifiers and by virtue of their actual importance in fiber optic technology will be treated elsewhere in detail.

We will now proceed to show the results of the combined Kerr and passive resonant nonlinear effects on the otherwise stationary solutions. Fig. 2 shows the spatial and temporal evolution of the same input pulse that in Fig. 1 when the

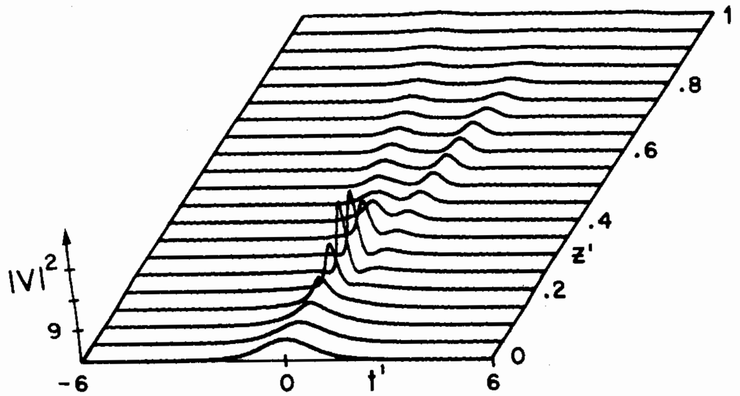

FIGURE 2. Spatial evolution of the same third-order soliton that is in Fig. 1, but including the resonant dynamics given in Eqs. (5) and (7). The relative resonant parameters were $\gamma = 0.57$, $B = 3.77$ and a normalized Gaussian distribution function $g(\Delta)$ of 2.0 unities width (FWHM) was used.

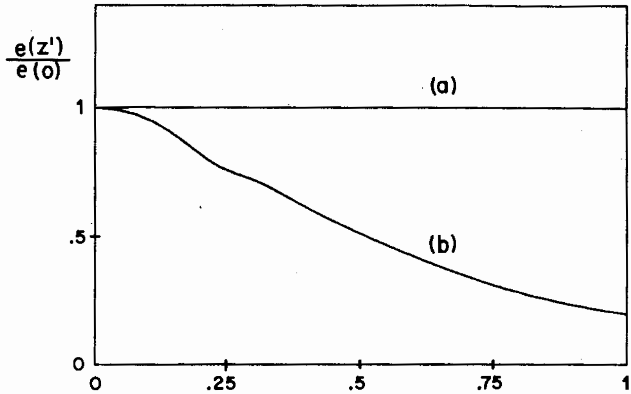

FIGURE 3. Spatial behavior of the relative pulse energy during the propagation through a) a typical single-mode silica fiber and b) a passive resonant doped fiber. The energy of the pulse, $e(z')$, is taken proportional to the integral $\int |V|^2 dt'$. The data was taken from the numerical simulations presented in Figs. 1 and 2.

resonant polarization of Eq. (7) is included. As it can be seen the symmetry of the pulse is broken during the propagation, indicating the presence of a dispersive modulation [13]. It is possible that this dispersion appears as a result of the competition between Ker and resonant nonlinearities, as it can be inferred from recent studies carried out on the inclusion of Kerr effect in resonant absorbers [15]. However, the induced asymmetry is not the only remarkable effect; the extreme narrowing of the ideal fiber soliton, which takes place at $z_0/4$ in Fig. 1, is diminished by the presence of the TLA, and also the restoration of the soliton after the period z_0 is inhibited. In fact, the input pulse in the doped fiber acquires a monotonic decay, where their

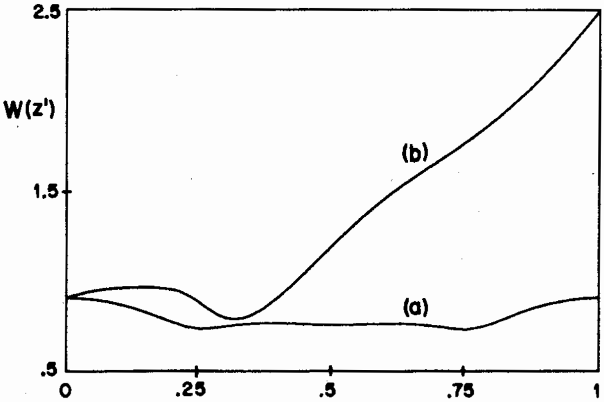

FIGURE 4. Spatial behavior of the temporal pulse width during the propagation through a) a typical single-mode silica fiber and b) a passive resonant doped fiber. The pulse width in a) describes an oscillatory evolution caused by the periodic behavior of the third-order soliton solution showed in Fig. 1. The pulse width, $W(z')$, is defined as $W(z') = [m_2 - m_1^2]^{1/2}$, where $m_i = \int t^i |V|^2 dt'/e(z')$.

energy loss during the propagation is taken by the TLA as excitation energy. Fig. 3 shows the relative energy carried out by the pulses of Figs. 1 and 2 during their propagation process. The loss and the rate of loss caused in the pulse by doping the fiber are clearly evidenced. If the TLA were absent, the energy of the pulse would follow an exponential decay in the presence of constant loss [2,6], in a similar way that the curve in Fig. 3b does for propagation distances $z' \geq 0.3$. Consequently, the influence of the TLA only is noted during the first quarter of the soliton period, where they try, without success, to sustain the lossless propagation.

A similar argument may be used to understand the broadening acquired by the pulse in the doped fiber, Fig. 4b. At the beginning the TLA behaves as if trying to maintain the stability, and in fact, a good pulse narrowing is still reached. But for $z' \geq 0.3$ the pulse has lost too much energy exciting the TLA ensemble and it is unable to support further stable propagation. The results presented here, however, should not be interpreted as discarding the use of passive resonant doped fibers for soliton-based telecommunication systems. Instead, they are the first results that show that it is necessary to control the transient propagation regime in the doped fiber in order to reach possible stationary regime. It is possible that such control can be accomplished by varying the propagation parameters. Any future results of these studies will be published later.

In conclusion we have proposed the use of single-mode silica-fibers doped with passive resonant TLA in an attempt to overcome the linear loss always present in an optical fiber. We have shown that the resonant doping causes, at least for the parameters we have chosen, a progressive spoiling in the otherwise stationary third-order soliton solution. However, more work must be done in order to be conclusive about the practical utility and viability of such doped fibers.

Acknowledgements

We would like to thank Dr. J.J. Sánchez-Mondragón for helpful discussions and M.C. Gabriel Arroyo-Correa and Mr. Jan Peter Isaksen for reading and commenting on the manuscript. Special thanks are given to the Instituto de Física de la Universidad de Guanajuato for facilitating their computational resources.

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Resumen. La propagación de pulsos en fibras ópticas monomodales a las que se les ha añadido impurezas resonantes es por primera vez analizada resolviendo numéricamente el conjunto completo de ecuaciones dinámicas para la fibra y para los átomos resonantes. Nuestros primeros resultados muestran que la presencia de dichas impurezas causa una pérdida y un ensanchamiento progresivo, destruyendo el comportamiento estable de un solitón óptico de tercer orden.